MONITORING

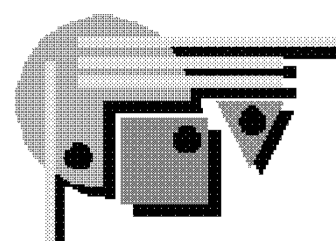
AND

PATIENT SAFETY

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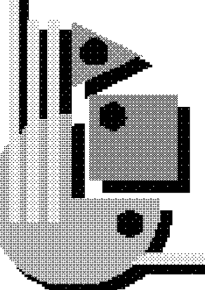
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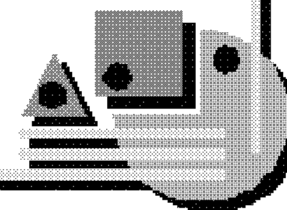


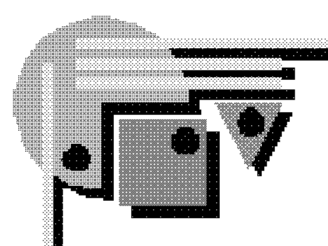
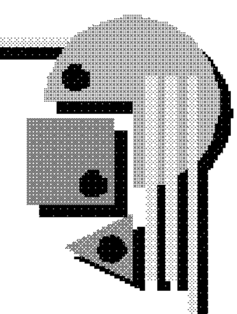
Foreword

It is HIM who has created the faculties of hearing (ears), seeing (eyes) and hearts (understanding) in the human-being, to make a faithful life – on earth – possible. The high quality of human life has been simply facilitated on earth through monitoring of surroundings by human senses. The structure of these senses has been always imitated by man to manufacture devices to monitor different vital and organ functions in health and during disease. Recently, physicians began to fix minimal monitoring standards for better management and care of their patients.

"Monitoring and Patient Safety" discusses anatomical and physiological classifications of monitoring systems with the conclusion that human monitors, gifted by ALLAH, are the actual controllers of high-technology monitors.



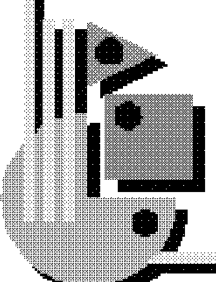
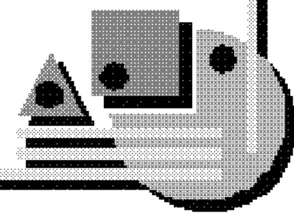


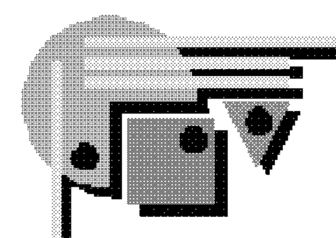
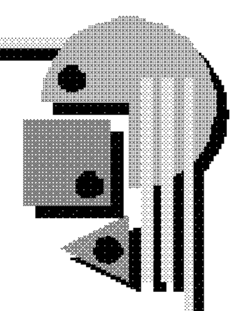



Dedication

"Monitoring and Patient Safety" is dedicated to the memory of those patients who died and for the apology to those patients who suffered due to the abuse of their human right of proper monitoring during their medical management.

Mohamed Ezzat Moemen

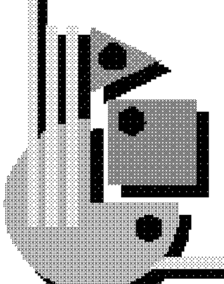
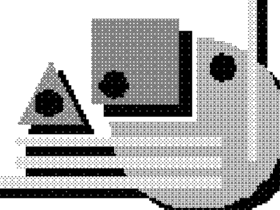



Acknowledgement

"Monitoring and Patient Safety" expresses profound appreciation to medical colleagues in many disciplines and from different nationalities, who made valuable contributions in the development of guidelines and algorithms of monitoring over decades.

Bio-engineers from different countries who participated in the establishment of the infrastructure and ergonomics of monitoring for patient safety deserve historical gratitude.

All patients who facilitated, during their medical management, the expansion of monitoring experience, are highly acknowledged.

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1 Introduction and Overview

1.1. Preoperative patient assessment
1.2. The anaesthetist versus hospital responsibility
1.3. The anaesthetic record
1.4. Classification of monitoring devices
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1. Introduction and Overview

Since the advent of modern anaesthesia, the anaesthetist relied on his/her natural senses to monitor the surgical patient, aided simply by a stethoscope and a sphygmomanometer. However, over the last few decades, there has been a progressive increase in the availability of monitoring devices. This enabled more major operations to be performed on sicker patients. However, although the anaesthetist is generally careful, conscientious and informed, s/he is usually blamed if a patient dies during or soon after operation[1, 2]. Some anaesthetists began to feel threatened and demoralized and began to employ the defensive medicine practices. Regrettably, this implied that the prime responsibility of the anaesthetist was to himself or herself rather than to the patient.

There is no doubt that the use of monitoring devices may yield information that adds to patient safety. But, there is also no doubt that many devices, if used inappropriately, may confuse and mislead the anaesthetist. There have been documented cases in which patients have suffered because the anaesthetist was distracted by a malfunctioning monitor. At the same time, if a patient dies during anaesthesia unattached to an available monitoring device, the anaesthetist is legally indefensible[3]. If such an opinion is accepted, it may lead to the widespread use of expensive complex devices with which anaesthetists are unfamiliar in circumstances in which their use may be unnecessary or even inappropriate[4]. This is because most anaesthetists support the concept that patients who suffer as a result of negligence should be compensated.

In spite of this, anaesthetists take pride in understanding equipment, and are keen to meet the challenge of the technological revolution and ensure that their patients receive the advantage of some of the recent advances in monitoring. However, inadequate monitoring had been considered a major or contributing factor in about one-fifth of all anaesthesia-related deaths[5-10].

In recognizing the role of inadequate monitoring in anaesthesia related morbidity and mortality, minimum monitoring standards for patient safety were published by different medical authorities. There is a general agreement that 70 – 80% of serious morbidity and mortality is caused by operator errors or by inadequate experience, training or knowledge [5–10]. In this context, training plays a major role in reducing perioperative complications. The need for education about monitoring and equipment has been recently established. This is because the proper management of the interface between biomedical technology and the patient presents a great challenge to the modern anaesthetist to achieve patient safety. As an example, anaesthesia related mortality in Australia has fallen over 25 years from one in 5-10.000 cases (which was currently the condition in USA)[10] to one in 26.000 cases through proper administration of training and education programs[12]. The need for such programs has been agreed upon by medical authorities in many countries. The advantages of computerizing anaesthetic records with common standards and pooling of data became evident. This would enhance education through quality assurance meetings for studying morbidities and mortalities and for decision-making and cost benefit analysis. This would also establish specific protocols

and strategies for prevention and management of problems and would allow to ensure the best value for each medical dollar and to ensure patient safety.

1.1. Preoperative patient assessment:

Clinical monitoring starts with preoperative assessment of the patient, to ensure that s/he is in the optimal state for anaesthesia and surgery. This consultation is ideally performed by the anaesthetist who is to administer the anaesthetic. Although early consultation is not always possible as before emergency surgery, it is still necessary in these circumstances. Day surgery patients should undergo screening sometime before surgery.

Preoperative patient assessment includes full history, clinical examination and necessary investigations and patient consent for anaesthesia and surgery. This should be documented in the patient record. There should be a minimum for preoperative investigations for each patient with the arrangement of blood if transfusion may be needed during surgery.

During preoperative patient assessment, history should cover many points. Demographic data include the age, gender and body weight. Medical problems and previous surgery should be interrogated. Complications related to previous anaesthesia for the patient or a member of his family should be explored. The patient should be asked about the presence of chest pain, exercise tolerance and breathing difficulties including the presence of cough, sputum, orthopnea, asthma and smoking habits. Medication history and allergic response to drugs should be known. Other data as the

presence of indigestion or reflux, pregnancy or previous deep venous thrombosis or any important items for the particular patient are explored. The results of any special investigations are encountered.

A clinical examination of the patient should be carried out and should include a general examination of the whole body together with measurement of the blood pressure (BP), heart rate (HR), respiratory rate (RR) and body temperature. Scoring of the airway is carried out for any difficulty of endotracheal intubation (ETT). Examination should include the precordium and chest as well as assessment of any positive medical findings by inspection, palpation, percussion and auscultation. Abdominal organs should be also examined. An inspection of any area into which the anaesthetist intends to inject a local anaesthetic drug should be carried out at the preoperative visit, as well as the veins to be used during anaesthesia.

The conduct of this preoperative visit is aided if appropriate investigations have been anticipated and the results are available at the time of consultation. An attempt should be made to satisfy the psychological needs of the patient and premedictation should also be ordered if considered necessary. Orders should be given regarding preoperative drug administration, food, fluids and prosthesis management. Arrangements are made for any further investigatory measures, for orders to continue medications, for consultation where appropriate with colleagues in other medical specialities and discharge after surgery if it is to be done as an ambulatory procedure.

A summary of this preoperative consultation should be included in the patients' anaesthetic record with a notation of ASA classification. There will be occasions when circumstances or the clinical condition of the patient require that anaesthesia and surgery proceed before fulfilment of these requirements. On such occasions, the anaesthetist and the surgeon should record reasons for the omission of recommended investigations.

1.2. The anaesthetist versus hospital responsibility:

Before commencing any general or regional anaesthetic, there should be a thorough check of all the equipment which may be needed. This should include checking all the equipment required for airway management, the suction, the monitors and all the drugs and syringes to be used. A ventilator must not be used in the absence of a functioning disconnection alarm. It is a fundamental requirement that any used device should be calibrated before use. The anaesthetist should be aware of the sensitivity, specificity and possible pitfalls of each device. If a crisis does occur, the anaesthetist will have the advantage that all the equipment used have been checked and calibrated.

Hospitals should have a policy governing the use of monitoring equipment, in order to minimize the risk of equipment-related hazards and inappropriate failure to maximize equipment accuracy and to increase the working life of devices. This means that all equipment, before use, must pass hospital "acceptance" and "safety" inspections. The hospital must have plans for routine safety checking, maintenance, calibration and repair of equipment in

the event of breakdown. All details should be documented under a specific "testing authority" such as a Biomedical Engineering Department.

The hospital engineering system is responsible for the supervision of the pipeline system for supply of oxygen, nitrous oxide, medical air and suction. It is also responsible for the electrical supply for the operating rooms. Monitoring of oxygen by oxygen analyzers can detect hypoxic mixtures and prevent disasters and this belongs to the responsibility of both the anaesthetist and the Biomedical Engineering Department. This adds to patient safety, if it is available on every anaesthetic machine. There should be alarms to warn of loss of oxygen or electric power.

1.3. The anaesthetic record:

The anaesthetic record serves as a "monitor" for both the patient and the anaesthetist. It has a number of important functions. It acts as preoperative, intraoperative and postoperative record for the operative procedure under general or regional anaesthesia.

The pre-anaesthetic record includes general patient information as name, age, sex, ward and record number, weight and height, blood pressure and pulse rate, proposed operation and time of last food or fluid. It also includes evidence of pre-anaesthetic assessment as significant medical or surgical history, anaesthetic history, relevant physical signs, results of investigations, current drug therapy, drug or other allergies, ASA class of the patient, premedictation orders and signature of the anaesthetist and date.

The intraoperative record should include names of anaesthetist(s), surgeon(s), assistant(s), premedictation given regarding timing and effect, details of the anaesthetic technique, timing and doses of drugs, timing and nature of volumes of fluids, gas composition and flow rates, airway management and difficulties, ventilation details, monitors employed, patient position during operation, details of operative events and any anaesthetic or surgical complications.

The regional technique should be also recorded including its type, the site of injection, the level of sensory loss, the type of the needle/catheter, the local anaesthetic used including its dose, volume, concentration and an adjuvant if used together with any comments.

The post-anaesthesia record should give evidence of adequate care for the patient until protective reflexes have returned and haemodynamic stability has been achieved, whether this care is given in the operating room, the recovery area or the intensive care unit. A signed safe recovery score allows the anaesthetist to transfer the patient from the recovery area.

The anaesthetic record documents vital signs, individual responses to drugs and to surgical stress and any difficulties, events or complications encountered. It is a document that may influence subsequent anaesthesia. It is an indispensable medicolegal document. It is a tool for the purpose of teaching and research. The postoperative visit after discharging the patient from the recovery room may reveal morbidity not evident at an earlier stage. This visit should be documented in the anaesthetic record.

1.4. Classification of monitoring devices

The word “monitor” is derived from the Latin word “monere” which means “to warn.” The word monitoring is used, in the clinical setting, to refer to repeated recordings of physical, physiological and emotional signs from a patient. Patients’ data are monitored with the goal of optimizing their care and detecting adverse events. Monitoring allows signal adjustment to prevent deterioration and achieve improvement of the patient condition. The continuous and accurate measurement of appropriate markers help to understand the problem and reach the diagnosis to indicate proper therapy. Monitoring delivers the ability to alert the physician, through alarms, about an event that may produce morbidity or mortality. A monitor can provide trends of measured signals that can indicate the progress of the parameter over time, and can thus provide information objectively about the patient outcome. Monitors provide the advantage of freeing the physician from routine data collection allowing more attention for patient care with medicolegal recording of patient progress.

The anaesthetist is the only completely indespensable patient "monitor", being responsible for the safety and well-being of the patient undergoing surgery under his/her care. Any monitor consists of three components:

1. The sensor which detects the parameter to be measured and generates an appropriate signal.
2. A system of data collection and organization which converts the signal into a recognizable and usable form.

3. A system which interprets and evaluates the information and assesses whether it lies within a predetermined range.

Each component may be "human" or may be some electrical or mechanical "device". This provides us with four classes of monitors[13] (table 1).

Table 1: Classes of monitors

Class	Sensor	Data collection / organization	Interpretation
I	Human	Human	Human
II	Device	Human	Human
III	Device	Device	Human
IV	Device	Device	Device

Currently, the most fundamental and important patient monitors are those which fall into classes I and II. Class III monitors still require human interpretation. Although class IV monitors are composed of devices for sensing, data collection and interpretation, they should work under the control of the human anaesthetist.

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2 Class I Monitors

2.1. Who owns the human senses
2.2. The Human Monitors
References

2. Class I Monitors

2.1. Who owns the human senses:

"Say: who provides you from the sky and the earth? Or who owns hearing and sight? And who brings out the dead from the living? And who disposes the affairs? They will say: 'Allah.' Say: 'Will you not then be afraid of Allah's punishment?'" (10:31)[1].

"And Allah has brought you from the abdomens of your mothers while you know nothing. And He gave you hearing (ears), sight (eyes) and hearts (understanding), so that you might give thanks (to Allah)." (16:78)[1].

"It is He, who has created for you (the sense of) hearing (ears), sight (eyes), and hearts (understanding). Little thanks you give (to Allah)." (23:78)[1].

"Then He fashioned him in due proportion and breathed into him the soul (created by Allah for that person), and He gave you hearing (ears), sight (eyes) and hearts (understanding). Little is the thanks you give (to Allah)." (23:9)[1].

"Till, when they reach it (Hell, Fire) their hearing (ears), their vision (eyes), and their skins will testify against them as to what they used to do." (41:20)[1].

"Say it is He who has created you and endowed you with hearing (ears), vision (eyes), and hearts (understanding). Little thanks you give (to Allah)." (67:23)[1].

"And indeed We had firmly established them with that wherewith we have not established you (O Quraish). And We had assigned them the (faculties of) hearing (ears), seeing (eyes) and hearts

(understanding), but their hearing, seeing and hearts availed them nothing since they used to deny the Ayât of Allah, and they were completely encircled by that which they used to mock at." (46:26)[1].

2.2. The human monitors:

Class I monitors represent "the human monitors" as all their components are human in nature in the form of human senses. For vision, the retina is the sensor, the optic nerve is the data collector and organizer and the brain carries out the interpretation. For hearing, the tympanic membrane is the sensor, the abducent nerve is the data collector and organizer and the brain performs the task of interpretation. Other human senses act as "human monitoring devices" in a similar way.

During the 1950's the use of human senses has been often described. Not only useful information was obtained visually and auditorally, but touch and smell became also important and anaesthetists have been satisfied with the sensing potentialities available to them. There is a strong evidence that until the second world war, only a minority of anaesthetists employed the stethoscope and the sphygmomanometer routinely during anaesthesia, depending mostly on human senses for monitoring their patients.

Sight as a "human monitor" can detect important information by observing the patient position on the operating table, the working anaesthetic machine and ventilator, the colour of the patient mucous membranes and blood, the response of the patient to the surgical stress, the warning alarms of monitors and the composition and

compatibility of drugs or intravenous fluids. Hearing as a "human monitor" may be used to detect sounds of excess gas escaping from the circuit valve with spontaneous ventilation and of circuit leaks. It may also discriminate between various audible device alarms. An ear to the chest can be used for auscultation. Touch as a "human monitor" by paplation can detect pulse rate, rhythm, character and volume and can assess sweating and the feel of the breathing bag. Again, by percussion, gastric distension and chest pneumothorax can be diagnosed. Smell as a "human monitor" may be used to check the nature and concentration of anaesthetic vapours and whether there are any major leaks. Taken together human senses represent the overall "human monitors" which are always available provided that the anaesthetist is near the patient and has an access to appropriate parts of his/her body. Monitoring devices are useful adjuncts, but they alone cannot replace careful observation by a vigilant anaesthetist [2].

In conjunction with the "human monitors", the patient can share as being a monitoring "device" for him/herself. This is not strange as a patient undergoing trans-uretheral resection of the prostate (TURP) under regional anaesthesia is exposed to the development of TURP syndrome. The intravascular absorption of large volumes of the irrigating fluid at the prostatic vascular bed during prostatic resection may lead to hyponatraemia. In this situation, the patient starts to be confused (without receiving sedation) denoting altered mental function. So, the syndrome is diagnosed early and measures are taken both to stop its progress and for its early management. Again diabetic patients undergoing surgery under regional

anaesthesia can monitor their extremes of the glycaemic state as hyperglycaemia or hypoglycaemia in the form of altered cardiovascular or brain functions in the absence of sedation. This alerts the anaesthetist to control the blood sugar level. Thirdly, a patient undergoing carotid endarterectromy under general anaesthesia needs monitoring to protect his/her brain from showers of emboli from the operative site as transcranial Doppler, EEG or recording of somatosensory evoked potentials (SSEP), without absolute safety. Such safety can be only absolute if this type of surgery is carried out under cervical plexus block with conscious sedation of the patient, being continuously observed by the anaesthetist with strong gentlemen cooperation between them to diagnose early expected embolic brain complications through both human monitoring "devices". So, carotid endarterectomy may be safely conducted under monitored anaesthesia care (MAC) and the patient acts as a human monitor for himself. Such a wakeful test allows continuous assessment of areas of the brain at risk (e.g. speech) that cannot be assessed by electrophysiological methods. The most critical period is that of temporary occlusion of the carotid arteries, but most patients can tolerate this occlusion through collaterals provided by the circle of Willis. Human monitoring by the wakeful test can help the patient with inadequate collateral circulation to prevent regional areas of brain ischaemia. A wakeful test in this situation is sensitive to blood flow reductions to 25 ml/min/100gm above levels of 15-20 ml/min/100gm [3].

The EEG and the somatosensory evoked potentials are only limited to the neural regions responsible for their generation [4]. This

wakeful testing method can, thus, provide information to identify the patient who requires an intraluminal shunt across the clamped carotid artery. Although some surgeons routinely insert shunts during endarterectomy, these shunts may induce some embolization and may also interfere with surgical exposure.

Awake testing has the capability to assess other neurological functions. A wake-up test was originally applied to scoliosis correction with Harrington rods and owed its value from one major event which occurred during the procedure [5]. Advances in surgical corrective techniques have changed the period of risk to cover multiple potentially deleterious events [6]. Therefore, a more continuous method of assessment was desirable to prevent potential neurologic sequelae during spinal surgery. Because SSEP assesses posterior spinal cord function, a non-noticed reduction in anterior spinal artery blood flow can produce ischaemia of the anterior regions of the spinal cord that induces motor weakness of the lower extremities. For this reason the wake-up test is being extensively used as a human monitor in addition to the SSEP during spinal surgery [7]. Briefly, patients receive nitrous oxide and short-acting narcotic / relaxant anaesthesia and potent inhalational anaesthetics are not administered. When needed by the surgeon, introperatively the wake-up test is performed by discontinuing nitrous oxide and within 3-5 minutes, neuromuscular blockade is proved to be relatively shallow (2-3 twitches on the train of four stimulation) and the patient should respond to verbal commands by moving his hands and feet, excluding spinal cord ischaemia. This test is easy to perform and is not psychologically traumatic to the patient because

it had been explained to him/her preoperatively added to the designed amnesia that prevents awareness [8]. Anaesthesia is resumed after demonstration of extremity movements.

Awake craniotomy for epilepsy surgery [9-11] and tumour resection[12,13] has been recently described and carried out. For cerebral cortex resection near the eloquent areas, awake craniotomy can facilitate speech mapping [14]. This is achieved by an anasthetic technique entailing propofol infusion for sedation and regional anaesthesia for supraorbital, supratrochlear, greater occipital, lesser occipital and auriculotemporal nerve blocks. After the cortex is exposed, the patient is awakened and functional testing is performed. The patient is encouraged to talk about a range of topics familiar and interesting to him/her and in this way the quality of his/her speech production is closely monitored. Disturbance of speech fluency is observed when the speech cortex is stimulated. When speech area mapping is completed, the patient is re-anaesthetized with propofol for the remainder of the operation. The patient breathes spontaneously throughout the procedure. Under the effect of fentanyl/benzodiazepine / propofol, a nosopharyngeal airway provides oxygenation and allows end-tidal carbon dioxide monitoring. In addition to this awake propofol technique, an asleep / awake/ asleep technique which secures the airway by fiberoptic endotracheal intubation has been described [15]. The anaesthetic sequence includes thiopentone or propofol, N_2O, oxygen inhalational general anaesthesia with local anaesthetic for the scalp.

A tube exchanger allows an awakened patient to be re-intubated and re-anaesthetized till the conclusion of the procedure.

Medical errors are reported to be the third most frequent cause of death in the UK. Studies in which the genesis of an error has been analysed suggest that human factors were responsible for 61% of adverse outcomes. System-based errors existing within the infrastructure of an organisation and forming the risk to the patient can contribute up to 85% of the untoward events in the perioperative period.[17] Human errors included errors in drug administration (24%), airway management (16%), improper use of anaesthetic machines (22%) and other categories (38%)[17]. So, clear lines must be established for the responsibility of the adverse effects, through clear programs for quality assurance and monitoring the quality of care.

The human monitoring ability of the anaesthetist can be employed for monitoring airway score, the Glasgow Coma Scale (GCS), the Trauma Score (TS) or the Visual Analogue Scale (VAS). This ability can also monitor hypovolaemia class according to the American College of Surgeon's Scale (ACSS). These are only few examples of the wide range of applications of the "human monitors".

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3 Class II Monitors

3.1. The stethoscope
3.2. The manual sphygmomanometer
References

3. Class II Monitors

Class II monitors introduce mechanical or electrical sensors to extend the human senses of the anaesthetist for monitoring vital functions of his/her patients. Sensing is achieved through a "device" while data collection and interpretation are "human" in nature. Examples of this class are the stethoscope and the non-automated sphygmomanometer.

3.1. The stethoscope:

At the beginning of the 19^{th} century diagnosis was largely based on a patient medical history and direct auscultation of an ear to the chest. This was thought by many physicians, to be disgusting and unethical with female patients. Such circumstances led Laennec, a French physician, to auscultate – indirectly with a paper rolled into a cylinder – a female patient whose age and sex made an ear to the chest auscultation unethical[1]. His success led to further experiments replacing the paper cylinder by wood, indian cane and other materials. This was accompanied by the introduction of a wooden stethoscope in 1819[1]. (Fig.1)

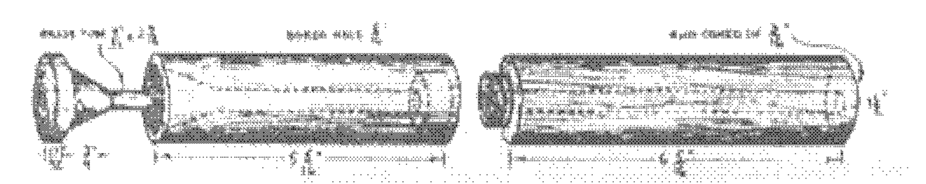


Figure1: Laennec's wooden stethoscope

Laennec aimed to facilitate the diagnosis of thoracic diseases[2]. But a plug added to the chest end of the wooden stethoscope facilitated listening to the heart. When the plug was removed a larger opening auscultated the lung. For closer listening the two halves of the stethoscope could be unscrewed[3]. By 1832, a stethoscope with a flexible tube of spiral wire covered by caoutouc cloth had been developed[3]. Many other designs during subsequent decades improved acoustic performance and convenience[3]. At the advent of clinical anaesthesia, generations of physicians and anaesthetists had been exposed to the stethoscopy discipline. Ultimately in 1893, Solis-Cohen described an oesophageal stethoscope, with the primary purpose for cardiovascular diagnosis[4] (fig. 2). Relatively recent reviews of stethoscopy examplify a high regard in which it continues to be held in the practice of medicine. Nowadays, an oesophageal stethoscope can be inserted to evaluate heart and breath sounds (i.e. bronchospasm and pulmonary oedema). A recent modification of the oesophageal stethoscope includes the incorporation of a thermistor to measure core temperature, two electrical leads to facilitate the recording of ECG and possibly two electrodes to enable transoesophageal cardiac pacing.

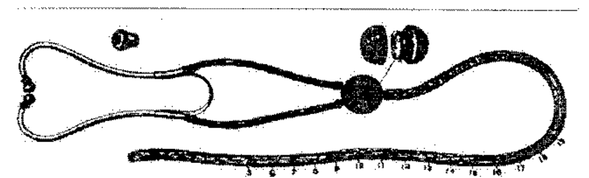


Figure 2: The oesophageal stethoscope described by Solis-Cohen in 1893 [4].

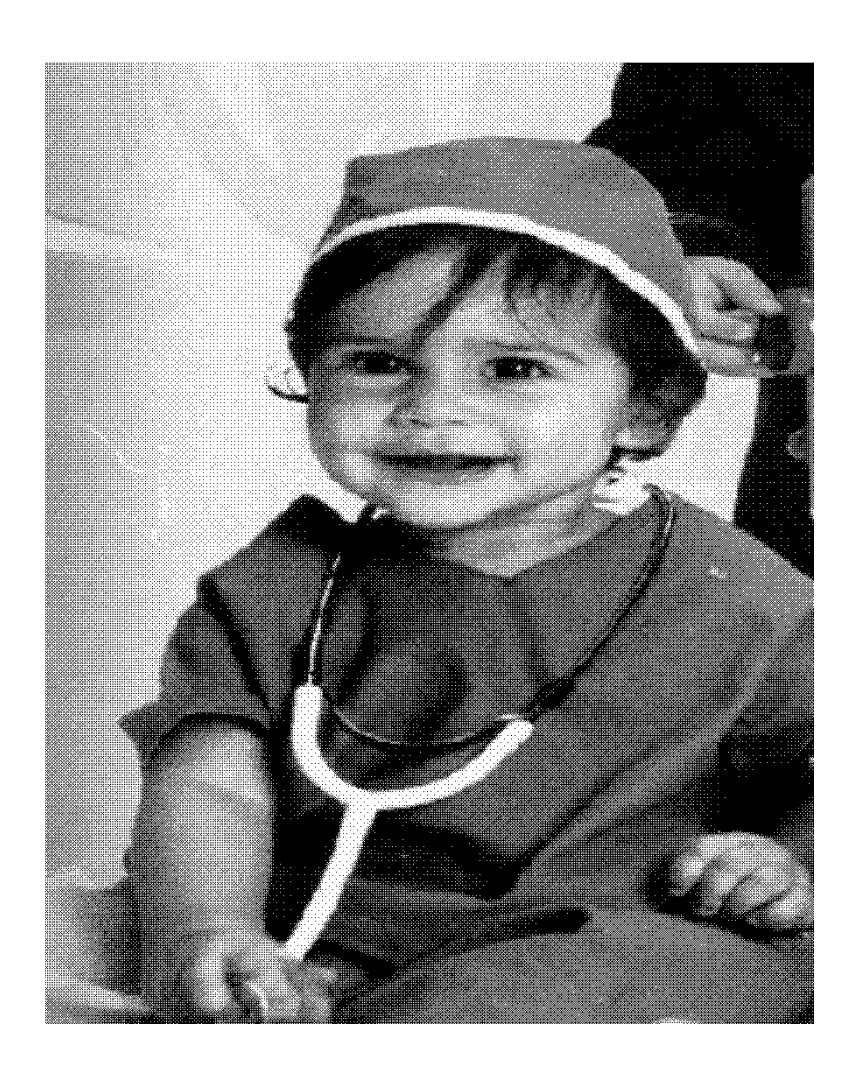


Figure 3: The stethoscope, the friend of the physician.

For anaesthetists, convenience of management with the currently used stethoscope was a real problem. (fig. 3) Long operations made anaesthetists restless with less tendency to auscultate the chest because many patients breathed spontaneously

during anaesthesia. Anaesthetists were also busy during controlled ventilation by their hands squeezing the anaesthetic bags that kept them immobilized at the head of the table. More recently, in 1983, a video display of stethoscopic information during anaesthesia was described but the ergonomic problem of auscultation in the operating room remained[5]. During this time the increasing availability of pulse oximetry and capnography reduced the anaesthetists' interest in stethoscopey. Actually, after the first description of the stethoscope, more than a century elapsed before being adopted in the operating room in a routine way[6].

The stethoscope allows continuous monitoring of the rate, rhythm and character of the heart beats and the rate, distribution and character of breath sounds. It may be placed on the precordium or in the oesophagus. It may confirm the proper position of the endotracheal tube or the nasogastric tube. Breath sounds may change with the onset of bronchospasm. Intraoperatively, a continuous use of a stethoscope, during paediatric anaesthesia, gives a continuous monitoring of the circulation on a beat by beat basis and of the respiration on a breath by breath basis. In conjunction with the manual sphygmomanometer, the stethoscope can facilitate BP measurement. So, it may be prudent to describe the stethoscope as a minimum monitoring standard for any anaesthetic procedure. The physician can consider the stethoscope a friend monitor, being mobile, cheap and easy to use.

3.2. The manual sphygmomanometer:

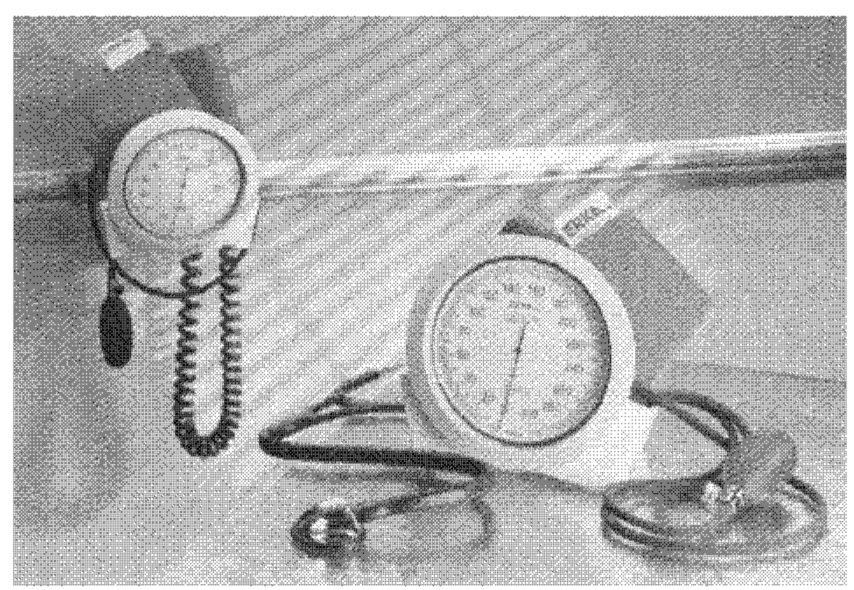


Figure 4: The manual, non-automated, non-invasive, indirect measurement of arterial blood pressure by the manual sphygmomanometer

In all patients, whether hypertensive or not, the BP should be measured around the time of the preoperative assessment of the patient, immediately before and after induction of general or introduction of regional anaesthesia, at regular intervals during maintenance of anaesthesia, on arrival and before leaving the recovery room and as often as appears necessary in the recovery room and the surgical ward. Routine measurements of the BP should be made using a non-invasive indirect method (fig. 4).

Care should be made to use a snugly fitting cuff of appropriate width of about 40% of the circumference of the arm (fig. 5). It is an acceptable practice during stable anaesthesia and

uneventful surgery to measure and document both systolic and diastolic BP and to document them on the anaesthetic record. It is important to realize that non-invasive BP measurement may yield errors up to 30% [7]. Mean BP can be calculated by adding one third of the systolic-diastolic difference to the diastolic value. Mean BP can be normal with marked peripheral vasoconstriction when no radial pulse is palpable, when Korotkov sounds are weak and when oscillations on the mercury manometer are nearly imperceptible[8]. Currently automated sphygmomanometers are used perioperatively and direct invasive BP monitoring has specific indications. However, a stethoscope and a manual sphygmomanometer should be available on every anaesthetic machine with different cuff sizes, and should represent a minimum monitoring standard for any anaesthetic procedure. The physician can consider the manual sphygmomanometer a friend monitor, being mobile, cheap and easy to use.

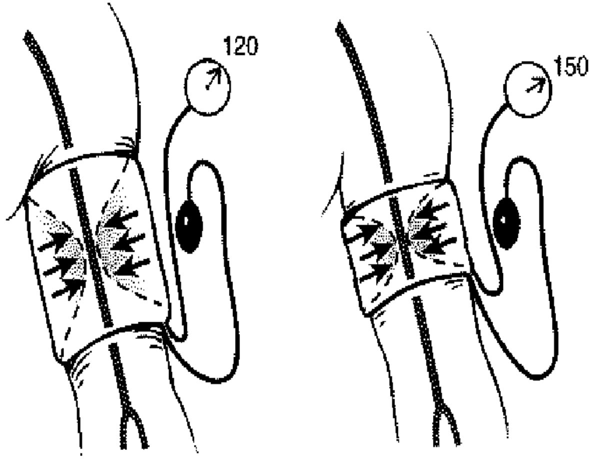


Figure 5: Correct arterial blood pressure monitoring (150mmHg) by a snugly fitting cuff of appropriate width of about 40% of the arm circumference.

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4 Class III Monitors

4.1. The automated sphygmomanometer

4.2. The invasive blood pressure monitor

4.3. The electrocardiogram

4.4. The pulse oximeter

4.5. The capnogram

4.6. The electronic thermometer

4.7. Monitoring neuromuscular transmission

4.8. Monitoring anaesthetic depth

4.9. Monitoring the brain and spinal cord functions

4.10. Echocardiography

4.11. Thromboelastography

4.12. The central venous and pulmonary artery catheters

4.13. Derived cardiorespiratory variables

References

4. Class III Monitors

Class III monitors can sense the information by a "device", collect and organize them by a "device" and present them to the anaesthetist for his/her human interpretation. These monitors may partially interpret the data by setting alarm limits if available. The anaesthetist has to check that the monitors are well-calibrated and the sensors properly placed for proper performance and correct interpretation. Examples are the non-invasive automated sphygmomanometer, the invasive cannula/ transducer/display arterial BP monitoring system, the ECG, the pulse oximeter, the capnogram, the electronic thermometer, the nerve stimulator, the monitors for anaesthetic depth, monitors for the brain and spinal cord functions, the echocardiogram, thromboelastography, the central venous and pulmonary artery catheters, the monitors for respiratory functions and gastric tonometry. Other haemodynamic and oxygen transport parameter monitoring can be also included.

4.1. The automated sphygmomanometer:

Automated sphygmomanometers can display systolic, diastolic and mean arterial BP. They can show trends of repeated BP measurements. Through setting alarm limits, they can alert the anaesthetist for serious changes of BP. (fig. 6) However, they may produce records as imprecise as those obtained by the manual method. In addition, they may be difficult to calibrate. When unexpected BP readings are obtained, it should be at least confirmed that the automated device is yielding results similar to those

obtained by a manual method. In a study of six automated devices, errors in mean BP ranged from -30% to +40% and five failed to meet a proposed standard in USA[1]. Further problems are that erroneous results are produced in patients with irregular dysrhythmias, that nerve palsies may be produced with frequent measurements for prolonged periods and that the device may "default" when needed most. However, the automated indirect sphygmomanometers are convenient, whenever they do not vary with the manual sphygmomanometers, as regular BP readings are provided when the anaesthetists are busy and whenever access to their patients is difficult.

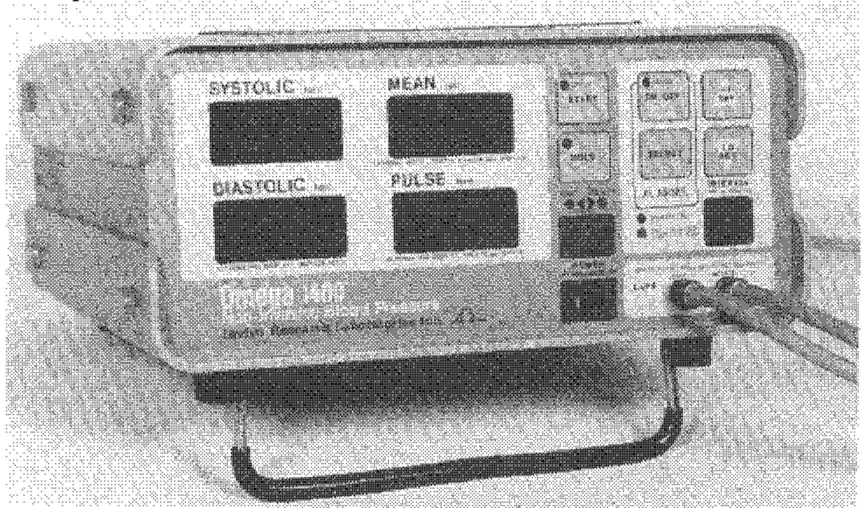


Figure 6: The automated sphygmomanometer

4.2. The invasive blood pressure monitor:

As all non-invasive methods of BP monitoring are imprecise, and they tend to become more so with high or low pressures[1], direct measurements from an intra-arterial cannula should be used if

accurate values are required. An intravascular cannula / transducer / amplifier / display system is indicated in seriously-ill patients, in patients with significant left ventricular disease or hypertension, in patients undergoing major or prolonged surgery, in patients in whom deliberate hypotension is planned, in those in whom sudden haemodynamic disturbances or susbstantial blood loss may occur and in obese or morbidly obese patients (fig. 7). Heparinised radial cannulation may be done in the non-dominant hand after performing modified Allen's test. A pressure transducer is used and calibration should be carried out before use, and care must be taken to use an identifiable zero-point on the patient. The pressure transducer / amplifier / recorder system is a useful monitor for patient safety when indicated.

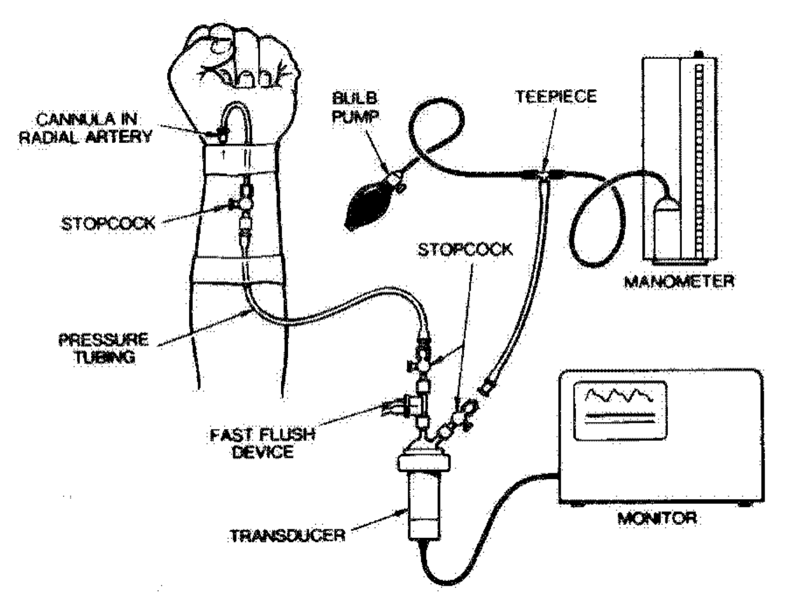


Figure 7: The pressure transducer-amplifier-recorder system for invasive monitoring of arterial blood pressure

In practice, a fluid-filled system comprising a 4cm 20-gauge non-tapered arterial cannula connected to a low volume displacement pressure transducer by non-compliant pressure tubing less than 100 cm long, a suitable three-way stopcock and a fast-flush device constitute an adequate system. Meticulous care must be taken to ensure that no air bubbles are trapped anywhere, and it is necessary to ensure that the amplifier – recorder system has an adequate response at a suitable band width. For amplitude measurements, a system capable of accurately reproducing sine waves at frequencies up to 20 Hz for a pen-deflection of 60 mmHg equivalent is adequate[2].

Having established that the measuring system as a whole has an adequate frequency response, its damping coefficient should be checked before each measurement. (fig. 8) This is necessary because the arterial cannula may be kinked or distorted, its tip may be impinging on the wall of the artery or be partially obstructed, there may be air in the fluid-filled connecting system, or there may be a stenosis in a connector or tap. Any or all these would reduce the resonant frequency and increase the damping coefficient of the system.

Accurate systolic and diastolic pressures are thus quite difficult and time-consuming to obtain. If the necessary steps have not been taken, it is of great importance to prevent the common practice of instituting treatment on account of the displayed blood pressures which are artefactually elevated by resonating catheter transducer systems. This requires great vigilance when the false values are prominently displayed. In practice, mean BP, in most

situations during direct BP monitoring, is a safe reading for BP monitoring and guiding therapy.

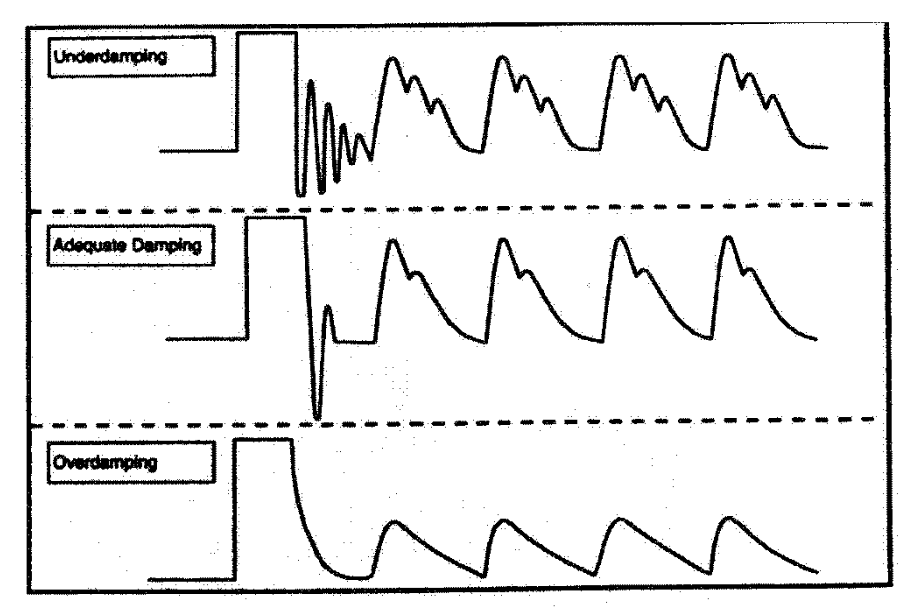


Figure 8: Undamped, adequately damped and overdamped arterial blood pressure tracing after a high pressure flush.

4.3. The electrocardiogram:

The electrocardiogram (ECG) represents the difference in electrical potential between two points on the body surface and an indifferent electrode, or between pairs of points. It provides a recording of the electrical activity of the heart in the vector of the chosen lead. It may be used as a rate-meter, to detect arrhythmias, to detect myocardial ischaemia or injury and as an additional monitor to have in place if problems are anticipated. Actually, it has been considered the front-line cardiovascular monitor for a long period of time (Fig.9).

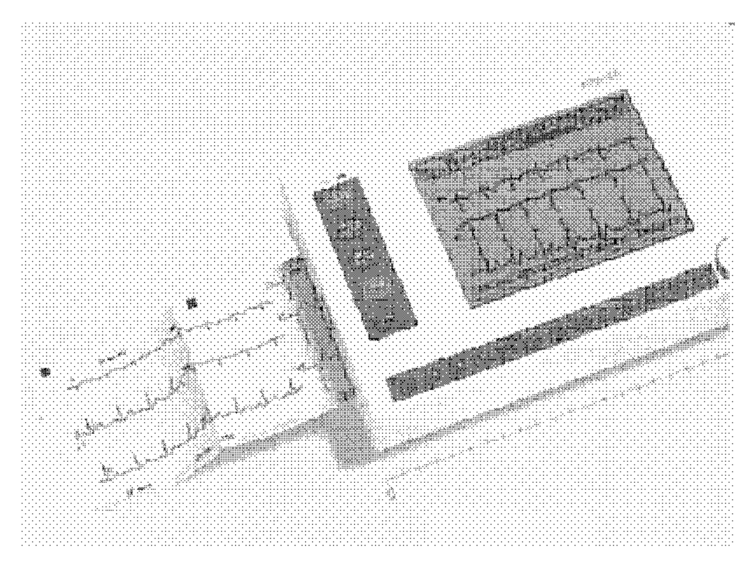


Figure 9: The electrocardiographic machine.

Standard ECG recordings are obtained from different combinations of chest and limb leads, each set recording from a different direction, and providing information about a different part of the heart:

- Standard leads:

Lead I: between right arm and left arm.

Lead II: between left leg and right arm.

Lead III: between left leg and left arm.

- Augmented unipolar leads (reference electrode is obtained by connecting all three):

a VR: right arm.

a VL: left arm.

a VF: left leg.

- Unipolar chest leads (reference electrode is formed by the combined a V leads) are shown in figure (10) :

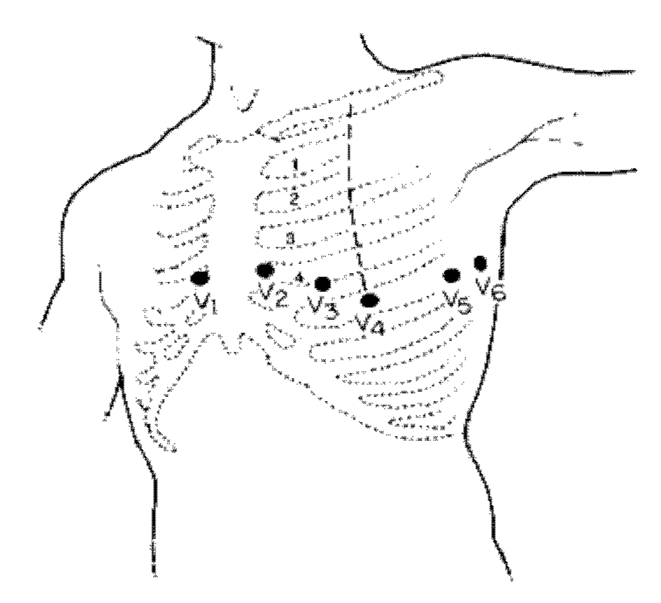


Figure 10: Normal sites of the V-electrodes.

V_1: 4th intercostal space, right sternal edge.
V_2: 4th intercostal space, left sternal edge.
V_3: midway between V_2 and V_4.
V_4: 5th intercostal space, left midclavicular line.
V_5: 5th intercostal space, left anterior axillary line.
V_6: 5th intercostal space, left midaxillary line.
V_7, V_8 and V_9 may be extended posteriorly at left posterior axillary line, left mid-scapular line and medial scapular border, while right V_2 to V_6 may be located on the right side in corresponding positions to the left electrodes. These additive

electrodes can help in diagnosis of conditions as clockwise rotation of the heart and dextrocardia.

The display is recorded onto an oscilloscope or moving paper. Frequency range is 0.5-80Hz. Magnitude of deflection is proportional to the amount of heart muscle, but reduced by passage through the chest. High skin resistance is reduced by cleaning the skin with alcohol. Electrodes are usually silver/silver chloride with chloride conducting gel to reduce impedance. Depolarization towards a lead (or repolarization away) results in a positive deflection, while depolarization away from a lead (or repolarization towards) causes negative deflection. Thus, in the normal ECG recording, polarity of deflection varies in the different leads.

The ECG may be used as a heart rate-meter in healthy patients, and to detect electrolyte changes (especially potassium) but, it gives no indication of the adequacy of the circulation. Baroreceptor and chemoreceptor functions may be both severely impaired under anaesthesia, while a regular unchanged trace is no guarantee that the patient is not profoundly hypoxic, hypotensive or hypercarbic [3].

In contrast to the ECG, the pulse oximeter gives better and more relevant information; better because the signal is not affected by diathermy, and more relevant, as the signal guarantees some adequacy of the circulation. A pulse oximeter does not require disposable electrodes and does not require a high degree of electrical isolation.

So, the ECG tracing is a record of the summed electrical vectors produced during depolarization and repolarization of the

heart. Electrical forces directed towards an electrode are represented as upward deflections, whereas forces directed away from an electrode are represented as downward deflections.

The standard representation of the cardiac cycle is seen in the ECG as the P wave, the QRS complex and the T wave (fig.11). The P wave represents atrial depolarization. The P-R interval represents the time required for an impulse to depolarize the atria, traverse the AV node and enter the ventricular conduction system (0.12-0.2s). The QRS complex represents ventricular depolarization (0.04-0.12s). Atrial repolarization is usually not seen because it occurs during the QRS complex. The ST segment represents the segment following ventricular depolarization and its elevation by >1mm or depression by >2mm may denote ischaemia. Ventricular repolarization is represented by the ST segment and the T wave. The ST segment is normally isoelectric and the point at which the ST segment joins the QRS complex is known as the J (junction) point.

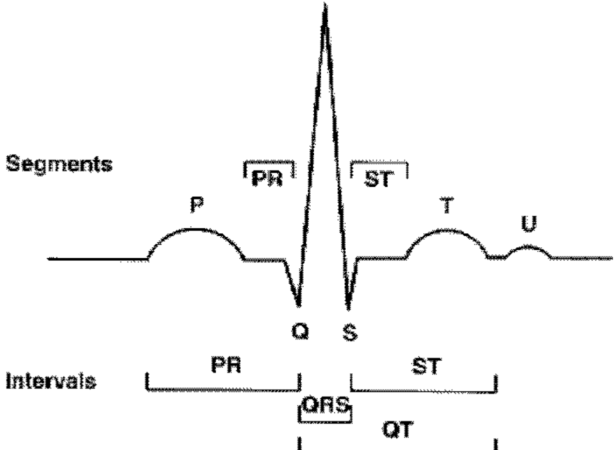


Figure 11: The normal electrocardiographic tracing.

For interpretation of an ECG record, the usual speed of recording is 25 mm/s and the usual calibration is 1mv/cm. The rate (beats/min) is calcualted by dividing 300 over the number of 5mm squares between successive QRS complexes. The rhythm is observed as regular or irregular and the irregularity is observed also if regular or irregular. P waves presence or absence and their regularities should be observed. The axis normally lies between -30°and +90°. Right axis deviation (>90°) may occur in normal subjects, in right ventricular hypertrophy, right bundle branch block or left posterior hemiblock. Left axis deviation (<30°) may occur in left bundle branch block, left anterior hemiblock or left ventricular hypertrophy.

Accurate analysis of rhythm strips requires experience, but the application of basic principles will allow the interpretation of most rhythms encountered and lead to a diagnosis, on which appropriate treatment is based.

The following systematic approach can be applied to the analysis of rhythm strips:

1. Is there an electrical activity?
2. What is the ventricular (QRS) rate?
3. Is the QRS rhythm regular or irregular?
4. Is the QRS complex width normal or prolonged?
5. Is atrial activity present?
6. How is atrial activity related to ventricular activity?

Any cardiac rhythm can be described accurately (eg, irregular narrow-complex tachycardia, regular broad-complex bradycardia, etc.) and managed safely and effectively using the first four steps.

Bradycardia exists when the ventricular (QRS) rate is less than 60/min (fig. 12). A first degree heart block is diagnosed when the P-R interval exceeds 0.2 seconds and may be physiological in trained athletes (fig. 13). A second degree heart block is present when not every P wave is followed by a QRS complex and dropped beats occur. There are two types of second degree heart block. In type I Mobitz or Wenckebach block, the P-R interval shows progressive prolongation with each successive beat until a dropped beat occurs (fig. 14). In type II Mobitz block, there is a constant P-R interval in the conducting beats but some of the P waves are not followed by QRS complexes (fig. 15, 16). In third degree or complete heart block, there is no relationship between P waves and QRS complexes as atrial and ventricular depolarization arise independently from separate pacemakers (fig. 17). If the normal cardiac pacemaker fails or operates abnormally slowly, cardiac depolarization may be initiated from a subsidiary pacemaker in the atrium, the AV node, the conducting fibers or the ventricle. The resulting "escape" rhythm will be slower than the normal sinus rate. A ventricular "escape" rhythm will be slower than a junctional rhythm arising from the AV node or bundle of His (fig. 18). An escape rhythm arising from ventricular myocardium is described as an idioventricular rhythm.

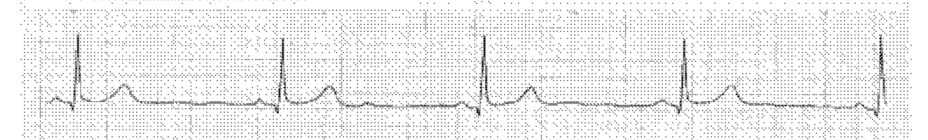


Figure 12 : Sinus bradycardia

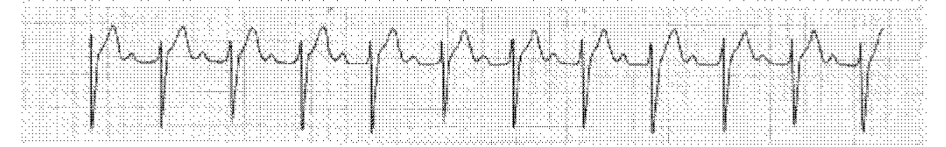


Figure 13 : First degree atrioventicular block

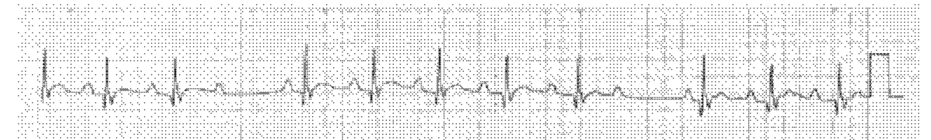


Figure 14 : Mobitz Type I or Wenckebach block

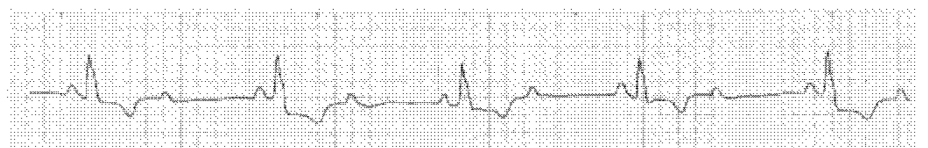


Figure 15 : Mobitz Type II second degree atrioventricular block (2:1)

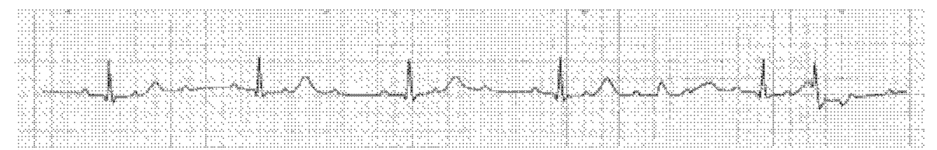


Figure 16: Mobitz Type II second degree atrioventricular block (3:1)

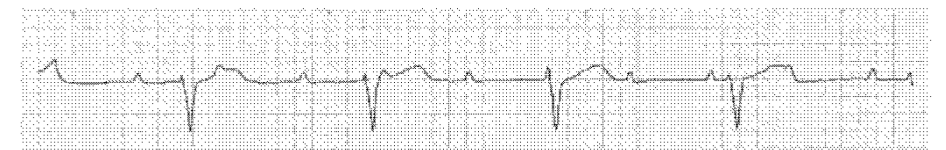


Figure 17 : Third degree (complete) atrioventricular block

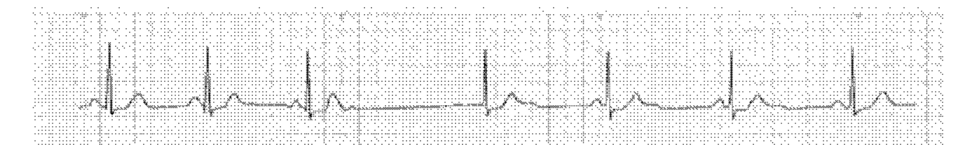


Figure 18: Junctional escape rhythm

Pathological tachyarrhythmias may arise from the atrium, the AV junction or the myocardium. They are either narrow or broad complex tachycardias. When a tachycardia arises from tissues situated above the bifurcation of the bundle of His, it is described as "supraventricular" (fig. 19). The QRS complexes will be narrow if ventricular depolarization occurs normally, but will be broad if conduction delay is present as with bundle branch block. QRS complexes may be regular if initiated by a single pacemaker or may be irregular in the presence of irregularly conducted atrial flutter waves or atrial fibrillation. Generally speaking, a tachycardia with narrow QRS complexes has a relatively favourable prognosis. However, it may cause acute decompensation in patients with chronic heart disease or severe angina in patients with coronary heart disease.

Atrial fibrillation is the most common arrhythmia encountered in clinical practice and is characterized by totally disorganized electrical activity of the atria (fig. 20). No recognizable P waves are seen in any lead. There is irregular atrial activity specially seen in V_1 and V_2 where a wave-form which is irregular in both amplitude and frequency is recorded. The QRS complexes are irregular and the P-R intervals vary unpredictably. There is no recongisable relationship between the QRS complexes and atrial activity. The ventricular rate is in the range of 120-160/min. Atrial fibrillation is associated with an underlying heart disease.

In atrial flutter, atrial activity is represented by a series of rapid f-waves at a rate of 200-300/min. These are best seen in inferior leads II, III and a VF where they have a "saw tooth"

appearance. The ventricular rate depends on AV conduction, but there is usually a 2:1, 3:1 or 4:1 block (fig. 21, 22). If the block is constant, the ventricular rhythm will be regular, but a varying block results in an irregular ventricular rhythm. Initially, the arrhythmias may occur in discrete attacks, but later they become more long lasting and may precede the onset of permanent atrial fibrillation. Like atrial fibrillation, atrial flutter is associated with an underlying heart disease.



Figure 19 : Supraventricular tachycardia

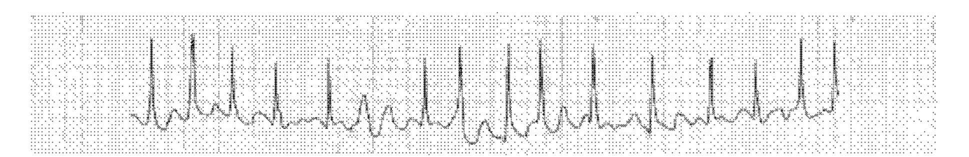


Figure 20: Atrial fibrillation



Figure 21 : Atrial flutter with 2: 1 atrioventricular block

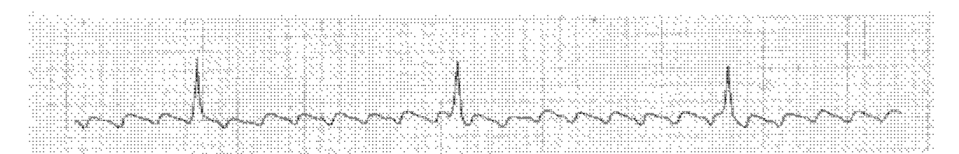


Figure 22: Atrial flutter with a high degree of atrioventicular block. F-waves are clearly visible.

Broad-complex tachycardias are the result of either a tachycardia arising in the ventricle below the bifurcation of the His bundle known as ventricular tachycardia (fig. 23) or a supraventricular tachycardia conducted aberrantly to the ventricles (right or left bundle branch block). The consequences depend on the rate and duration of tachycardia.

Ventricular tachycardia can degenerate into coarse or fine ventricular fibrillation, particularly when presenting with a rate of 200/min or higher (fig. 24, 25). All broad complex tachycardias should be treated as ventricular tachycardias unless there is a very good reason to believe that they are supraventricular.

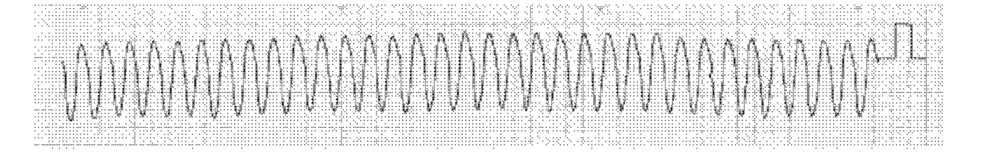


Figure 23 : Ventricular tachycardia

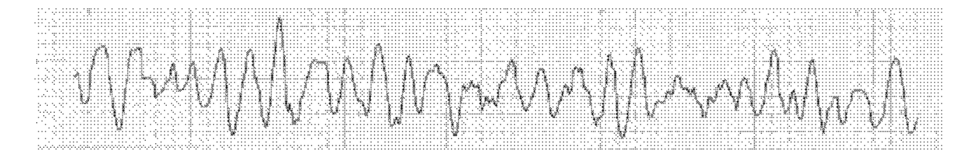


Figure 24: Coarse ventricular fibrillation

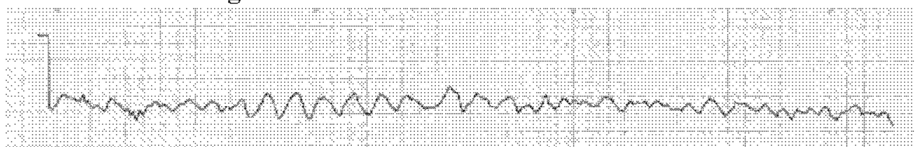


Figure 25: Fine ventricular fibrillation

In some patients accessory pathways exist between the atria and the ventricles, along with the normal AV node and His bundle which may also conduct atrial depolarization to the ventricles. The abnormal pathway may lead sometimes to abnormally broad QRS complexes. These patients are also prone to attacks of paroxysmal tachycardia. Sometimes, atrial fibrillation may result in a ventricular rate that is so fast that the cardiac output falls dramatically. The ECG appearances are of very rapid, broad complex tachycardias that may show marked variability in the QRS complexes. The commonest variety is seen in the Wolf-Parkinson-White Syndrome (WPWS) – due to the bundle of Kent in addition to the A-V node – where the QRS complex shows a delayed start, giving rise to a slurred upstroke of the R waves (delta waves). Overall, the rhythm is more organized than ventricular fibrillation and lacks the random activity of variable amplitude (fig. 26).

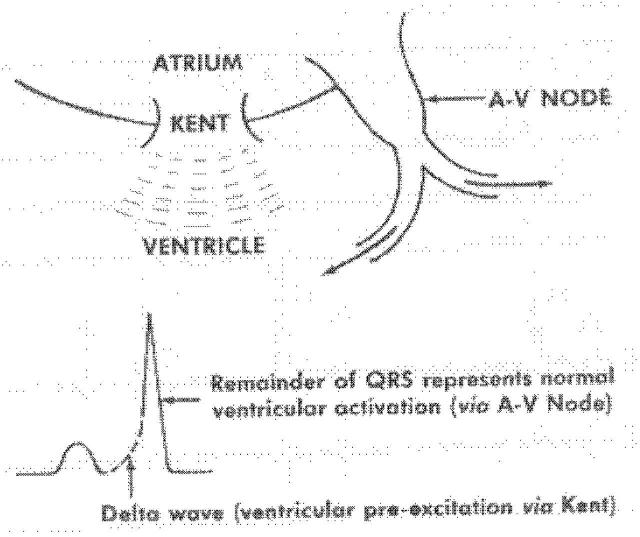


Figure 26: Wolf-Parkinson-White syndrome.

The characteristic appearance of ventricular tachycardia and fibrillation is usually easy to recognize. These are the only rhythms which do not require the systematic rhythm analysis. Ventricular tachycardia may suddenly degenerate to ventricular fibrillation. Pulseless ventricular tachycardia is managed in the same way as ventricular fibrillation by application of shocks. One important variety of ventricular tachycardia is Torsades de Pointes (twisting of points) in which the axis of the electrical activity changes in a rotational way so that the overall appearance of the ECG on a rhythm strip produces a sinusoidal pattern (fig. 27). This arrhythmia usually arises in patients with prolonged Q-T intervals. Although this can occur as a heriditary phenomenon, more commonly it is caused by drugs, including anti-arrhythmics. Many patients are hypokalaemic and/or hypomagnesaemic. Torsades de Pointes ventricular tachycardia may degenerate to ventricular fibrillation and cardiac arrest. Prevention of complications by correcting electrolyte imbalance is a life-saving measure.

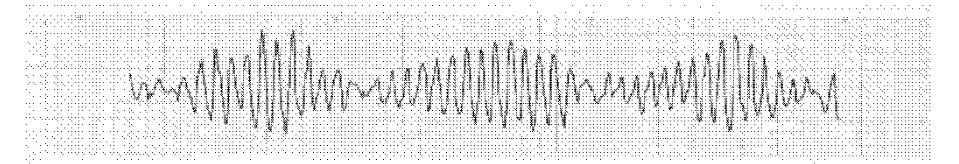


Figure 27: Torsades de Pointes

The ECG may be used to detect dysrhythmias. Standard lead II is usually the best lead as its vector is parallel to the net depolarization vector of the atrial wave, and hence usually shows the P-wave best.

In the usual ECG recording, leads V_4 and V_5 are anatomically close to the normal left ventricle and are useful in monitoring anterior wall ischaemia. This region is supplied by the main left anterior descending or circumflex coronary artery. Leads II, III and aVF view the heart inferiorly and display the electrical activity of the area of the myocardium supplied mainly by the right coronary artery. Some areas of the heart are difficult to monitor. Right ventricular dysfunction associated with inferior ischaemia is difficult to detect using standard leads and is probably best observed by a lead in the fourth intercostal space in the right midclavicular line. Posterior ischaemia is even more difficult to monitor using surface leads and the best way is the use of an oesophageal lead which produces a good P-wave deflection.

Although the ECG is widely used for detecting myocardial ischaemia (down-sloping of the ST segment more than 1.0 mm from the baseline), it, unfortunately, suffers from poor sensitivity and specificity. Changes in the ST segment may be produced by factors other than ischaemia, and some patients with ischaemia do not have ECG changes. With the use of lead V_5 during exercise, it has been claimed that about 90% of the ST segment and T-wave changes are detected [4]. This may be the case with the use of three lead ECG where 90% of ST segment changes will be due to lead V_5, 6% due to lead II and around 4% of the changes due to a third lead [5]. A three lead system is usually more convenient than a five lead system for ST segment analysis [5]. However, Modified V5 (the left arm lead in the V5 position) can be used to detect antero-lateral ischaemia with the monitor on the lead I setting, or to detect inferior wall

ischaemia with the monitor on the lead II setting. CM5 (left arm lead in the V5 position, right arm lead on the right sternal border, and the leg lead on the left shoulder) is the most comprehensive method to monitor ischaemia using three leads as it detects ST segment changes more frequently than other three-lead configurations. Still, in this case, a transoesophageal echocardiography (TOE) will give more consistent information of the ischaemic condition, as it may also show segmental wall-motion abnormalities (SWMA). Some patients with SWMA may develop perioperative myocardial infarction without showing ST segment changes in the ECG.

For preoperative assessment of myocardial ischaemia, 12-lead ECG, ambulatory ECG and exercise ECG are different types for diagnosis added to an ECG for ST segment analysis. Positive ECG findings may be of important clinical value in monitoring patients with coronary artery disease (congestive heart failure, myocardial infarction, unstable angina) or those who are prone to coronary artery disease (hypertension, diabetes mellitus, peripheral vascular disease).

Monitoring for patient safety does not require the use of ECG as a front line monitor for every healthy patient as the disadvantages may outweigh the advantages. Firstly, there is some risk that the ECG may provide a false sense of security as an unchanged ECG is no guarantee that the patient is not hypoxic, hypotensive or hypercarbic[3]. Secondly, savings on disposable ECG electrodes can be put towards purchasing other useful equipments. Thirdly, although ECG monitors are often used to detect ischaemia, they are

frequently used in a manner unlikely to achieve this goal. If the anaesthetist considers why, how and when the ECG should be monitored, then ECG monitoring may become more fruitful. However, it would seem to be inappropriate to devote funds to the purchase of ECG machines and expensive electrodes for use on every healthy child and young adult when pulse oximeters can do a cheaper job of patient cardiovascular and respiratory monitoring because the expenditure on disposable electrodes alone would represent at least half the cost per anaesthetic of a pulse oximeter. In all situations the cost / benefit ratio of any monitoring device should be considered.

4.3.1. Heart rate variability:

Heart rate variability (HRV) or the variation of heart rate (HR) around its mean value, through oscillations in the instantaneous HR, can be used as a window into some aspects of cardiorespiratory control mechanisms [6]. Fast fluctuations or high frequency (HF) variability is related to parasympathetic activity, while slow fluctuations or low frequency (LF) variability is related to sympathetic activity [6]. The balance between parasympathetic and sympathetic activities by the ratio of HF to LF powers has been clinically used both perioperatively [7] and in the premature infant [6] to examine cardiorespiratory control mechanisms.

Spectral analysis of the R-R intervals can quantify the components of the beat-to-beat variability. The area under the power spectral curve in a particular frequency band is considered to be a measure of the variations in HR at that frequency.

The major cardiorespiratory mechanisms behind HRV are: respiration (respiratory sinus arrhythmia), BP (baroreceptor reflex) and thermoregulation (peripheral vascular resistance).

From a variety of physiological experiments, it has been demonstrated that the inspiratory inhibition of vagal parasympathetic tone causes HF fluctuations in HR related to respiration in the form of centrally mediated respiratory sinus arrhythmia. Low frequency and very low frequency fluctuations are thought to largely result from thermoregulatory changes in the peripheral vascular resistance [8].

Baroreceptors also contribute in HRV. With deep inspiration, a large negative intrathoracic pressure is produced. As a result, large thoracic capacitance vessels expand causing blood to be pooled in the lung and vena cava. Venous return to the heart is transiently decreased inducing a brief fall in cardiac output and arterial BP and a reflex increase in HR through the carotid and aortic baroreceptor feedback loop. As the intrathoracic pressure increases with expiration, a bolus of blood returns to the heart and arterial BP increases and a reflex HR slowing occurs [9].

HRV can be measured by the time or frequency domains. The time domain involves measurement of statistical variations in R-R intervals between QRS complexes [10]. With the advance of personal computers and improvements in digital signal processing techniques, power spectral analysis has merged as a useful mathematical tool to determine moment – to – moment oscillations in HR.

The frequency domain power spectral HR analysis is a Fourier analysis of the R-R interval versus time function. Data are transformed from a quantity varying over time to an amplitude varying over a range of frequencies.

A continuous sequence of ECG data is converted to R-R intervals and instantaneous HR. The signal is then sampled, digitized and passed through a fast Fourier transformer to discern the inherent frequencies associated with rhythm oscillations of HR. In this way, the R-R intervals in the time domain are converted into three frequency domains.

The respiratory peak coincides with HR oscillations due to respiration (respiratory sinus arrhythmia) and is typically centered about 0.25 Hz. It varies from person to person as a function of the respiratory rate. The LF peak usually occurs between 0.05 Hz and 0.15 Hz and is the same frequency (approximately every 10 seconds) described for BP recordings [9]. The very LF peak found between 0 and 0.04 Hz represents much slower fluctuations in HR that may be related to thermoregulatory or humoral mechanisms.

Analysis of beat-to-beat HRV has been described as a technique that may indicate cardiorespiratory responses of the autonomic nervous system and how it may be altered during anaesthesia and surgery [11].

HRV has been used as a simple non-invasive monitor to measure autonomic activity and alterations in such activity may be related to various disease states [12].

It has also been suggested that the changes in HRV specifically respiratory sinus arrhythmia might provide an index of

anaesthetic depth[13, 14]. Induction and maintenance of general anaesthesia were shown to cause a marked reduction in HRV [15].

All components of the HRV power spectra were reported to decrease with general anaesthesia and to increase during the recovery period [8]. In a study including 58 surgical adults, Ireland et al [7] found HRV to decrease with increasing age, weight, complexity of the surgical procedure, the use of reversal agents for neuromuscular blockade and the use of beta-blocking drugs, while it was not affected by morphine administration. More research is needed to facilitate the use of HRV measurements for perioperative patient monitoring on a wider scale in the future.

4.4. The pulse oximeter:

Oximetry was developed in the 1930's, when spectrophotometry was first used to measure the differential absorption of red and infrared light by mixtures of haemoglobin and oxyhaemoglobin. It was conceived in Japan in the 1970's [16] and further developed in the United States in the 1980's [17].

Pulse oximeters use two light emitting diodes that emit light at specifically selected wavelengths; 660nm (red), 940nm (infrared) and stabilizing circuits to ensure consistent light output. Each diode switches on and off at about 700 Hz and a single broad band photodiode detects the transmitted light and compares with the background light. A microprocessor determines the amounts of background red and infrared light reaching the sensor in both systole and diastole.

A microprocessor considers only the pulse-added signal produced by each pulse under the sensor and the differential absorption at the two light wavelengths. From these it calculates the percentage oxygen saturation of the arterial blood. Saturation values are assayed over a few seconds and are usually displayed, graphically and audibly (fig. 28). Pulse oximeters are usually accurate to 2% in the range of 70-100% haemoglobin saturation, when the sensors are receiving a satisfactory signal [18].

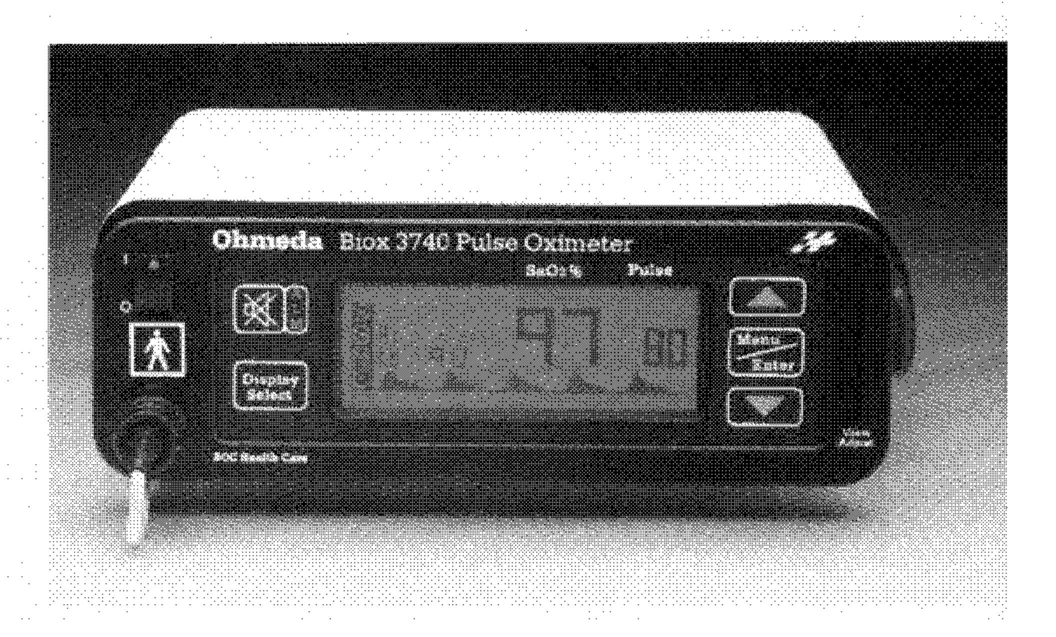


Figure 28: The pulse oximeter

To make the principle of oximetry more clear, light passing through tissues containing blood is absorbed by tissue as well as arterial, capillary and venous blood. Usually only the arterial blood

is pulsatile (fig. 29). Light absorption may therefore be split into a pulsatile component (AC) and a nonpulsatile constant component (DC). Haemoglobin oxygen saturation may be obtained by the application of the following equation:

$$S = \frac{AC_{660} / DC_{660}}{AC_{940} / DC_{940}}, \text{ where:}$$

S = haemoglobin oxygen saturation, AC_{660}, AC_{940} = pulsatile component of absorbance at 660 and 940 nm wavelengths, DC_{660}, DC_{940}= corresponding steady state components.

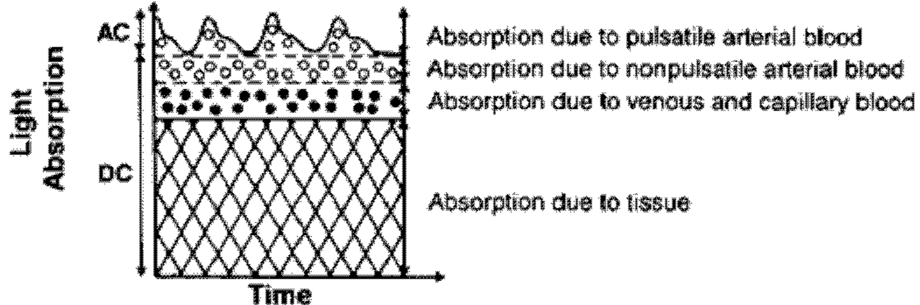


Figure 29: The principle of pulse oximetry

Pulse oximeters use non-invasive sensors with choice of attachment sites as the finger and the ear-pinna in adults or the bridge of the nose and the dorsum of the foot in paediatrics. Probes of different sizes are sometimes available and a little warm-up time is needed. Most pulse oximeters are programmed to check their internal calibration and sensor function at switch-on and intermittently during use. However, an anaesthetist can calibrate the monitor by applying the sensor to his own finger before use. Set-up alarm limits are usually activated by switching the monitor on.

Most pulse oximeters give a continuous audible indication of each pulse with the tone being modulated by the degree of saturation, which can provide an index of the reliability of displayed saturation values on a beat by beat basis. Interference from skin pigmentation or jaundice is usually minimal[17]. Oximeters can be battery operated, are of different sizes and are easy to transport with the patients. A pulse oximeter may be included into a multimodal monitor to be of ergonomic benefit.

Pulse oximetry has some limitations during use. As an adequate pulse is needed, gross hypothermia, vasoconstriction or hypotension may result in signal loss[18]. Movement artifacts caused by a shivering patient, or movement of the sensor or lead may obscure the pulse signal. Venous congestion from cardiac failure or in a dependent sensor site, or venular pulsations from tricuspid regurgitation may cause low saturation readings[19]. Synthetic finger-nails interfere with light transmission and saturation readings and dirt or adhesive on the sensor may depress the saturation values [20-22]. Gross anaemia with haemoglobin less than 59%, results in an inadequate signal and dyshaemoglobins, such as methaemoglobin or carboxyhaemoglobin, are not distinguished from oxyhaemoglobin[23]. However, abnormal haemoglobins can be recently differentiated from oxyhaemoglobin by fracitonated co-oximetry. Pulse oximeters therefore report functional saturation which is the percentage saturation of the haemoglobin that is available for combination with oxygen and not found to be dyshaemoglobin. A heavy smoker will have 10% carboxyhaemoglobin in his circulation by the end of the day[24]. This leaves 90% of his haemoglobin available for

combination with oxygen. As the percentage of available haemoglobin that is saturated with oxygen is reported as haemoglobin saturation by the pulse oximeter, this will result in 2.5% overestimation of haemoglobin saturation when 90% of the available haemoglobin is indeed saturated. Intravascular dyes such as methylene blue and indocyanine green may cause false low readings for a few minutes after injection [25]. Oximeter probes placed in well-perfused tissues such as the pharynx, trachea, cheek, nasal septum and tongue may provide accurate readings in such situations.

Complications from pulse oximeters have been so far limited to occasional signal failure and rare false saturation values as mentioned. No burns have been reported with the currently available unheated pulse oximeter sensors.

Pulse oximeters are used to advantage as continuous, non-invasive, rapid response monitors of arterial blood oxygenation in all patients during the perioperative period and in patients in intensive care units, specially those with respiratory or cardiovascular disease. A pulse oximeter is now considered the front-line monitor as it displays oxygen saturation together with displaying pulse volume, rate and rhythm, compared to the ECG which only displays the electrical activity of the heart. It, also, acts as a second-line monitor of oesophageal intubation and ventilator disconnection. As it may draw attention to life-threatening situations during anaesthesia, its routine perioperative use is recommended. This monitoring device is necessary when oxygen delivery may be unreliable, when patients are at risk of hypoxia and when lighting or

patient access is poor. Special indications for the use of pulse oximetry include sharing the patient airway with the surgeon in dental or head and neck surgery and during endoscopy. Patients who are heavily sedated or unconscious and being transported to the recovery room are also at risk and need monitoring of their oxygen saturation as well as during their stay in the recovery room. Oxygen saturation by pulse oximetry forms an important pillar for recovery and discharge scores. In rare but important situations, pulse oximetrs may be used for checking the circulation of re-implanted limbs or digits, for monitoring patients with sleep apnoea, and for monitoring patients during haemodialysis.

In conclusion, pulse oximeters present an excellent opportunity for patient safety. They provide monitoring on a beat by beat basis of heart rate, rhythm and volume, and of the saturation of haemoglobin in arterial blood. However, they do not replace an oxygen analyzer on the inspiratory limb of the breathing circuit which monitors machine and circuit function and they do not provide the information supplied by capnography or by disconnection alarms. It is true that no other monitor is equal to a pulse oximeter which non-invasively and safely provides a continuous indication of adequate circulatory and respiratory functions. So, it should be considered a minimum monitoring standard, for patients during perioperative care and in intensive care units.

4.5. The capnogram:

Capnometry implies the measurement of carbon dioxide (CO_2) in the gas phase and capnography implies the instantaneous

display of the CO_2 waveform. Currently, available airway CO_2 analyzers utilize one of the following principles to measure CO_2 in the inspired and exhaled gases on a breath to breath basis and display the CO_2 waveform: mass spectrometry, infrared absorption spectrometry and Raman scattering.

In the operating room, capnography is used for continuous CO_2 waveform analysis from patient intubation to extubation and it is sometimes used in the recovery room (fig. 30).

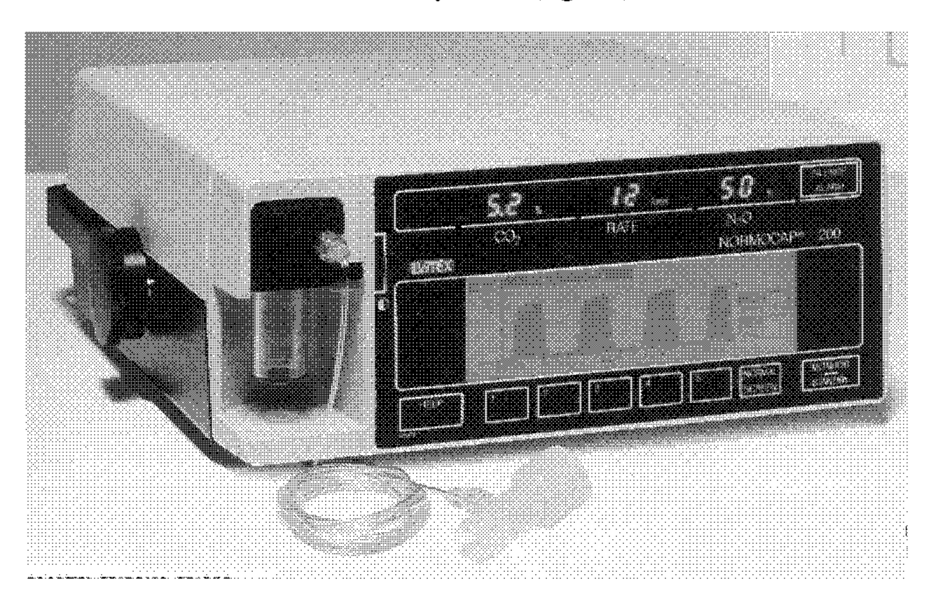


Figure 30: The electronic capnometer

Most electronic capnometers measure CO_2 by sending a beam of infrared light through an airway adaptor on the endotracheal tube as a main stream or in-line device or through a flow of gas sampled from the airway as a side-stream device. CO_2 strongly absorbs infrared light at a wavelength of 4300nm. The

amount of infrared rediation absorbed is proportional to the number of CO_2 molecules i.e. the partial pressure of CO_2. Inspired and expired CO_2 form a square wave, with a zero baseline unless there is rebreathing. Using the rise and fall of CO_2 during the respirtory cycle, monitors are designed to measure the respiratory rate. The capnometer may include the trend pattern of repeated CO_2 values overtime and alarm limits that can be set for both high and low values. Side-stream spirometry using a flow-volume monitor provides flow-volume or pressure-volume curves on-line as well as routine spirometric data added to capnography.

In the normal capnogram, The CO_2 wave-form shows a base line, an ascending portion, a plateau and a descending portion (fig.31):

NORMAL CAPNOGRAM

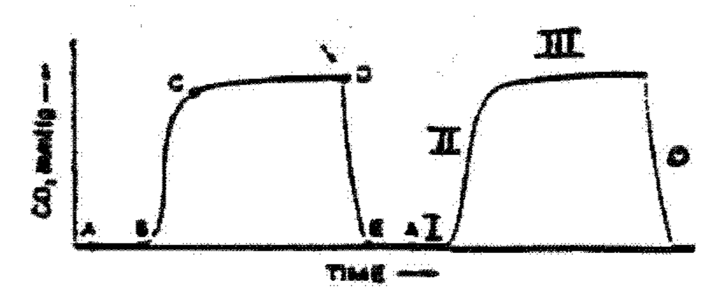


Fig. 31: The normal capnograph: A: exhalatory pause begins. A-B: clearance of anatomical dead space (phase I), B-C: dead space air mixed with alveolar air (phase II); C-D: alveolar plateau (phase III), D: level of $PETCO_2$ and beginning of inspiratory phase, D-E: clearance of dead space air (phase 0), E-A: inspiratory gas devoid of CO_2. Phases I-III represent expiration, while phase 0 represents inspiration.

B-C represents expiratory upstroke, and when prolonged it mostly denotes upper or lower airway obstruction with slow emptying of CO_2. C-D represents alveolar emptying of CO_2 with its extreme at the end-tidal period with $PETCO_2$ representing near $PaCO_2$. This is usually displayed as a plateau. If the plateau has a steep slope, it denotes increased expiratory resistance. If it is a biphasic waveform, it denotes incomplete paralysis or lungs with different mechanics. D-E represents an inspiratory downstroke. When this downstroke is prolonged, it denotes a leak in the breathing circuit or a malfunctioning inspiratory valve and slow ventilation may be expressed by cardiac oscillations. Elevated baseline of the capnogram denotes rebreathing of CO_2 due to incompetent expiratory valve, possible incompetent inspiratory valve or exhausted soda-lime canister (fig. 32a-b).

Measurement of end-tidal carbon dioxide concentration by the capnogram can detect many equipment and patient-related problems which other monitors alone may either fail to detect or may detect so slowly that patient safety may be compromised. Measurement of expired CO_2 gives an excellent indication of the patient's cardiovascular, respiratory and metabolic status (fig. 32a-b).

Increased $PETCO_2$ points to increased endogenous CO_2 production due to sepsis, fever, excessive catecholamines, shivering, convulsions, thyroid storm, total parenteral hyperalimentation, tourniquet release from big vessels or release of an aortic clamp. Malignant hyperpyrexia is a rare but important cause of high $PETCO_2$ which is also valuable for its diagnosis and during its

management. Increased $PETCO_2$ may be due to exogenous CO_2 administration as during CO_2 insufflation for laparoscopy or iv administration of sodium bicarbonate. Hypoventilation is a usual cause for increased $PETCO_2$.

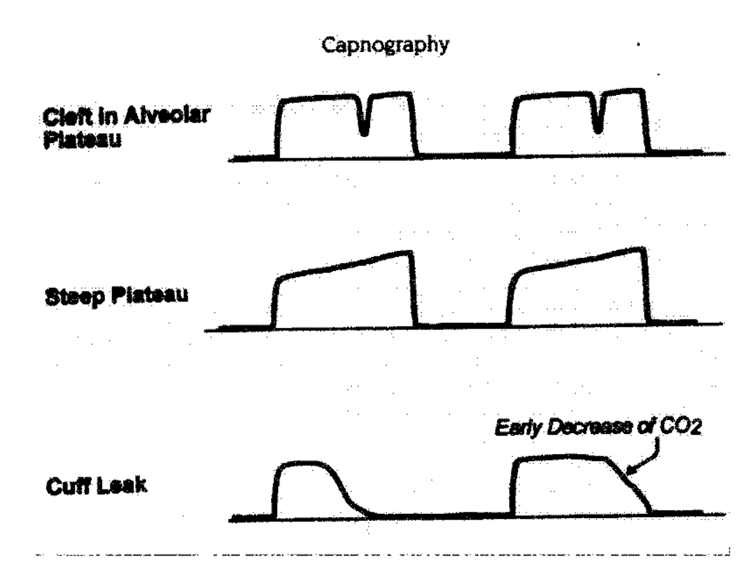


Figure 32a: Some abnormal capnographic patterns

Decreased $PETCO_2$ may be due to hypotension specially progressing to shock and cardiac arrest. It may also be due to metabolic acidosis or airway obstruction. Obstruction to the pulmonary circulation due to different patterns of pulmonary embolism causes varying degrees of reduced $PETCO_2$. Absence of $PETCO_2$may be due to oesophageal intubation, unintentional extubation, disconnection in the breathing circuit, upper or lower airway obstruction, pulmonary embolism, cardiac arrest or monitor failure (fig. 32b).

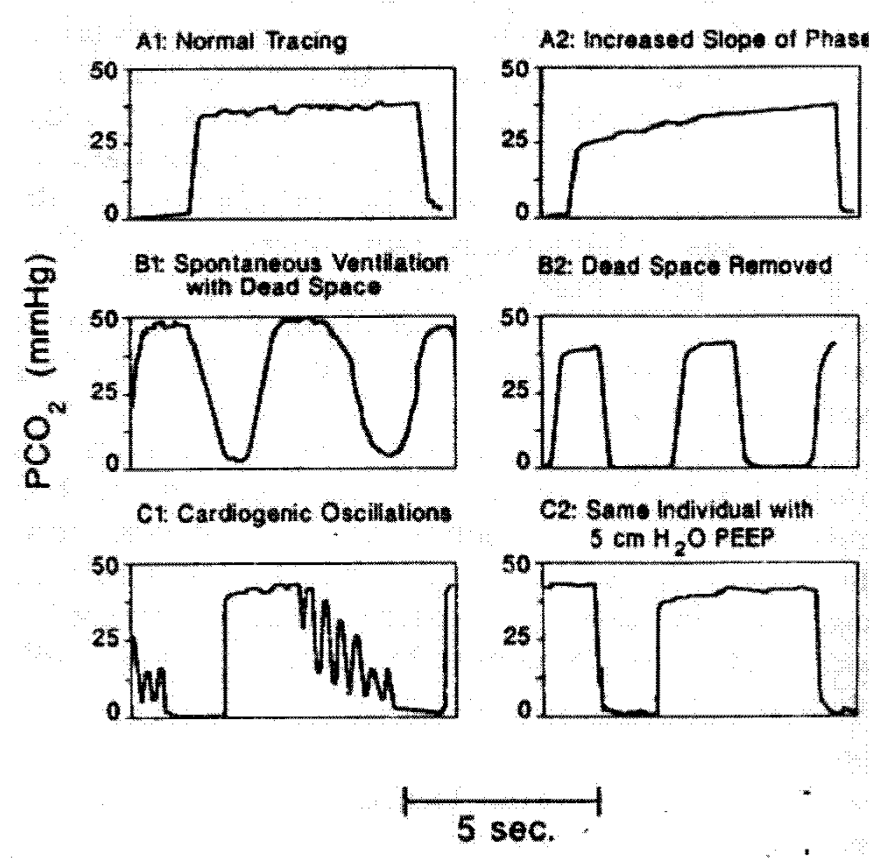


Figure 32b: Some abnormal capnographic patterns
Examples of capnograph waveforms. (A1) A normal tracing. (A2) An increased slope of phase III, usually representing uneven gas mixing within the lung. (B1) Spontaneous ventilation with added dead space. After removal of the dead space inspired CO_2 concentration decreases to 0 and the upstroke and downstroke of the waveforms become sharper because of less mixing (B2). (C1) Rapid oscillations of expired CO concentration due to cardiac action. (C2) The same patient after application of 5 cmH_2O PEEP. The abolition of cardiogenic oscillations by PEEP is probably due to an effect of increased lung volume.

$PETCO_2$ values of >10mmHg as a start point for resuscitation of cardiac arrest denotes a good prognosis and is useful for guiding the management.

In the clinical studies of anaesthetic accidents leading to death or significant cerebral damage, one of the major causes identified has been inadequate management of the airway [26]. Oesophageal intubation seems to be the commonest mishap. Apart from seeing the ETT passing through the vocal cords, the most reliable determination of its placement is by the measurement of CO_2 in the expired gas. With accidental placement of the ETT in the oesophagus, CO_2 may be detected on the capnogram screen for the first few breaths because of the accumulated expired CO_2 in the stomach during vigorous manual ventilation via a face-mask. However, the concentration rapidly decreases and thus the diagnosis is made easily.

A common mishap which occurs with a correctly placed ETT is kinking or displacement. If the CO_2 wave-form is observed on the screen, the diagnosis can be easily made for partial kinking of a tube as a new or exagerated steep sloped plateau. Displacement of the ETT down the trachea into one of the main bronchi during intermittent positive pressure ventilation (IPPV) will result in a sudden drop of $PETCO_2$. This may be impossible to diagnose with either a low pressure ventilator alarm or a precordial or oesophageal stethoscope.

In clinical studies the $PETCO_2$ display can be used to estimate arterial carbon dioxide tension ($PaCO_2$) non-invasively[27-28]. With limitations, $PaCO_2$ can be used as an indicator for clinical

purposes as measuring hypocapnia in patients with raised intracranial pressure. In the clinical setting $PETCO_2$ may also act as an apnoea monitor in patients breathing spontaneously during general anaesthesia. Side-stream analysers can be used to monitor not only the $PETCO_2$ but also the respiratory rate and rhythm. By the same way, the capnograph can act as a disconnection monitor and may be a rough, guide for reversal of muscle relaxants.

Monitoring for air embolism is a very important aspect of anaesthetic management in certain surgical procedures, particularly those performed in the sitting position [29]. Monitoring of $PETCO_2$ relies on a significant change in the pulmonary circulation for the detection of air embolism. A sudden drop in pulmonary blood flow due to a decrease in cardiac output under constant minute ventilation will cause a sudden drop in the $PETCO_2$. However, other clinical and monitoring techniques should be adopted by both the anaesthetist and the surgeon.

Assuming constant minute ventilation, any change in CO_2 production will be reflected in the $PETCO_2$. The most sudden and dramatic increase in CO_2 production occurs with malignant hyperpyrexia[30-31]. This change precedes the rise in patient temperature which, along with other nonspecific signs as tachycardia and cyanosis, are early clinically detectable signs. The early diagnosis and treatment of malignant hyperpyrexia are important for favourable patient outcome, and in addition, an abrupt decrease in $PETCO_2$ may signal control of the crisis and provide an end-point for the administration of dantrolene[30]. Other causes of sudden rises in $PETCO_2$ include rapid administration of blood or

bicarbonate and the release of arterial clamps on the aorta and big vessels or tourniquets on the extremities. However, these rises are usually expected, short-lived and are related in time to these events.

Observation of the waveform of a capnogram can alert the anaesthetist to diaphragmatic movement, which may be a problem in ophthalmic or neurosurgical procedures. This may be detected before the return of a visible muscle twitch from a peripheral nerve stimulator.

Measurement of $PETCO_2$ in addition to diagnosing disconnection of the ETT can diagnose disconnection of the inner tube of a Bain circuit which may lead to very high levels of inspired CO_2. It can also alert the anaesthetist to exhaustion of soda lime in her/his machine.

For proper clinical use of capnography, the device should be functioning properly, the tidal volume should be large enough to displace dead space, fresh gas flow rates are low enough to prevent dilution of CO_2, sample site is close to the airway and sample aspiration flow rate does not interfere with ventilation or cause air entrainment. In this way, capnography has proved to be a valuable addition to the armamentarium of the anaesthetist which can alert him/her to life-threatening conditions if being familiar with the device and its calibration.

Recently, dual or differential capnography is of important promising clinical use in thoracic surgery. Again, sublingual capnometry has been recently advocated as a technically simple and non-invasive monitor. It involves placement of a micro-electrode carbon dioxide sensor under the tongue facing the sublingual

mucosa. A recent study evaluated its use as an early indicator of systemic perfusion failure in critically ill patients [32].

However, it should be considered that the division of a time capnogram into inspiratory and expiratory segments is arbitrary and results in the inability of a time capnogram to detect rebreathing instantaneously. Demarcation of a time capnogram into inspiratory and expiratory components using gas flow segments was recently shown to facilitate prompt detection of rebreathing [27]. A Novametrix capnogram plus respiratory profile monitor (Novametrix Medical systems, Wallingford, CT) has been used to obtain a simultaneous display of CO_2 and respiratory flow waveforms on a computer screen during spontaneous and controlled ventilation using a circle system with the inspiratory valve competent (no rebreathing) and with the valve incompetent (rebreathing). A comparison was, then, made between the two waveforms to determine the inspiratory segment (phase 0) and the expiratory segment (Phase I, II, III) of the capnogram. The end of expiration almost coincides with the down slope of the CO_2 waveform in the capnogram when there is no rebreathing. However, in the presence of rebreathing, the alveolar plateau is prolonged and includes a part of inspiration (phase 0) in addition to the expiratory alveolar plateau (phase III). Note that phases I, II, III and 0 on the CO_2 display represent the A-B, B-C, C-D and D-E segments respectively. Figures (33a,b) show the respiratory flow rate waveforms and capnograms recorded during spontaneous and controlled ventilations.

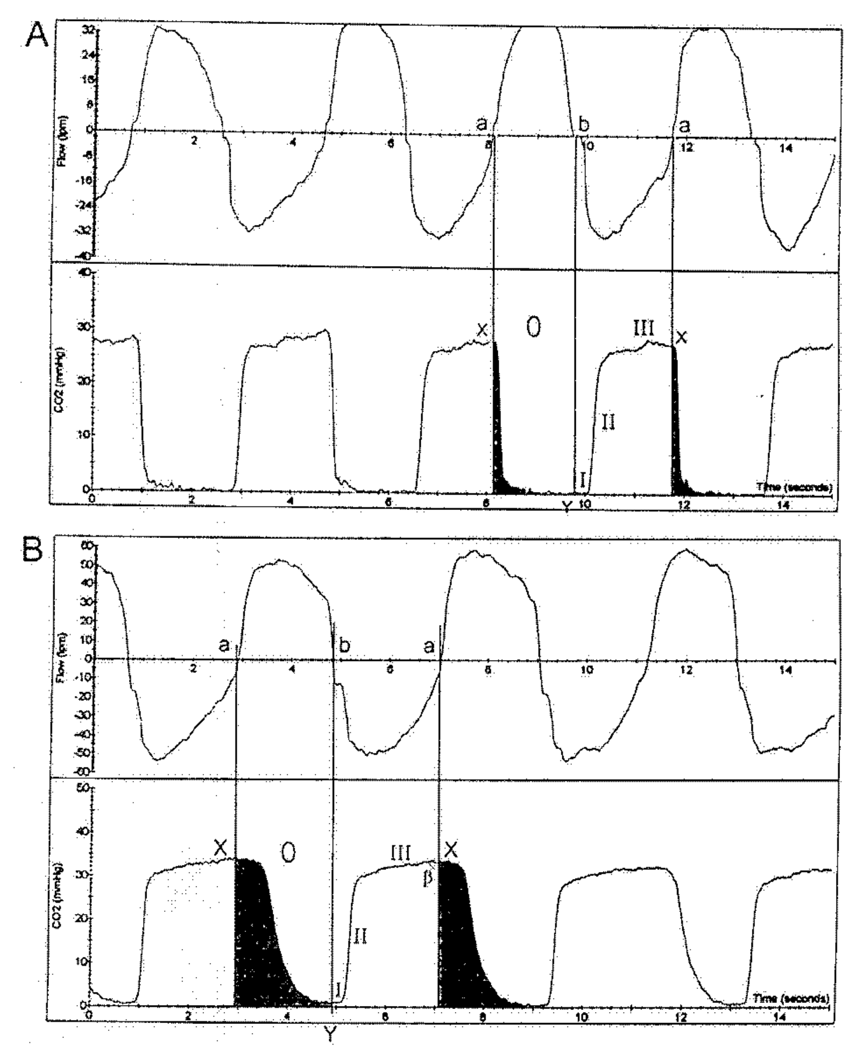


Figure 33a: Respiratory flow rate waveforms and capnograms recorded during spontaneous ventilation with A, inspiratory valve competent and B, valve incompetent in the circle system. ab = inspiration; ba = expiration; XY= inspiration; YX=expiration; 0, I, II, and III = phases

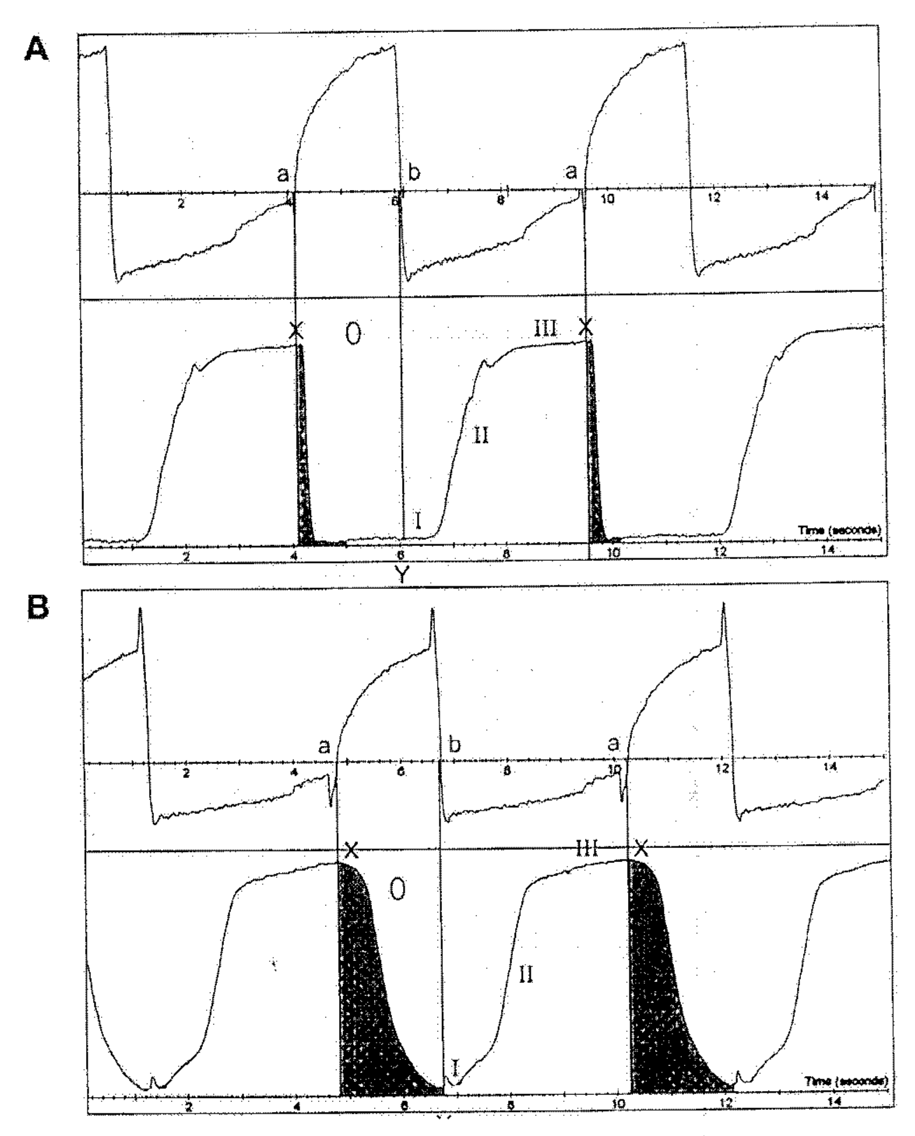


Figure 33b: Respiratory flow rate wave-forms and capnorams recorded during controlled ventilation with (A): inspiratory valve competent, and (B) valve incompetent in the circle system. ab = inspiration; ba = expiration; XY= inspiration; YX=expiration; 0,I, II, and III = phases

4.6. The electronic thermometer:

The body consists of a central warm core which includes the skull, thorax and abdomen, and a peripheral shell where the temperature is lower. Core temperature is maintained by a complex interplay of heat production, heat conservation and heat loss. As all may be affected during anaesthesia, body temperature (core, shell or both) should be measured when it is likely that it may change significantly, and it may be necessary to take steps to minimize heat loss and to warm the patient and any blood, fluids or anaesthetic gases that may be administered. The core temperature is usually maintained between 36° and 37.5°C, whereas the shell or skin temperature may be much lower. A core temperature below 36°C may have a number of undesirable consequences. It may delay awakening and the return of reflex functions, contribute to postoperative respiratory depression, lengthen the time required in the recovery room, or lengthen the required period of postoperative mechanical ventilation.

Measurement of body temperature is highly recommended during neonatal and paediatric surgery of substantial duration and during protracted surgeries in adults, particularly with exposed body cavities. It is also indicated for all surgeries in which large volumes of blood and/or fluids are administered and for all patients undergoing surgeries with deliberate cooling and rewarming. It is also necessary for hypothermic or hyperthermic patients or for patients with a suspicion of malignant hyperthermia. It is also desirable for elderly patients during general or regional anaesthesia.

Methods used for temperature measurement are either electrical as the thermocouple and the platinum resistance wire or non-electrical as the mercury liquid thermometer and the bimetallic strip. Electronic probe thermometers may be used in a variety of sites to measure core temperature, e.g. rectum, lower oesophagus, nasopharynx, tympanic membrane, through pulmonary artery catheter, or urinary bladder. Rectal and oesophageal probes are currently the most popular because nasopharyngeal probes may cause bleeding and tympanic membrane probes have a risk of perforating the ear drum.

Mean skin and mean body temperatures have been calculated using the following formulae [33]:

Mean skin temperature = 0.3 (upper arm + chest temperatures) + 0.2 (thigh+ calf temperatures).

Mean body temperature = 0.66 (urinary bladder temperature) + 0.34 (mean skin temperature).

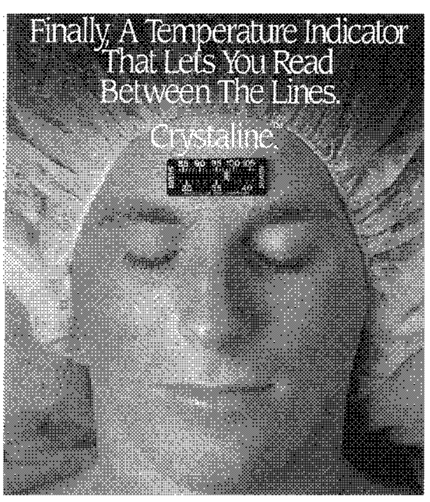


Figure 34: Monitoring skin temperature

Monitoring skin temperature (fig. 34) is also useful and correlating skin and core temperatures may be valuable. If both records are high, the patient is hyperthermic; if both are low, s/he is hypothermic and a high core-shell difference may refer to intense peripheral vasoconstriction that may indicate early shock.

Ideal ambient temperatures are those at which minimal variations in heat loss and heat gain are needed to maintain normal core temperature. A comfortable working temperature of healthy, active, lightly clothed adults is around 20°C with 50-60% humidity. However, an unclothed adult requires an environmental temperature of 29°C to maintain body temperature in the neutral range. As the mechanisms of temperature regulation and heat production of anaesthetized patients are remarkedly impaired, they tend to cool [34]. The environmental temperature required to provide a thermoneutral environment for neonates is from 32° to 35°C depending on gestation time and birth weight[35]. Infra-red heaters can be used to warm neonates, but skin and core temperatures must be monitored to prevent them from being hypothermic or overheated. As hypothermia is harmful, overheating also has the risk of haemolising transfused blood, water intoxication and infection from humidification, thermal injury or burns. Anaesthetists should be encouraged to use warmed fluids and to use low fresh gas flows, closed circuits and effective heat and moisture exchangers whenever possible. The ambient temperature should be raised when there is a serious risk of cooling, e.g. paediatric surgery, burns and major trauma. These measures are inexpensive, reliable and make additional warming measures unnecessary.

Heat-retaining mattresses, prewarmed before use, may continue to supply heat to patients for longer than is required and may cause an excessive rise in body temperature unless they are removed. If used when skin temperature is low, burns may occur. Mattresses through which warmed or cooled water are circulated are preferable. Whenever temperature monitoring has been used in the operating room, it should be continued postoperatively until repeated measurements are within the normal range. If the use of warming devices has been considered necessary during operation, prevention and correction of heat loss should be continued into the postoperative period.

4.7. Monitoring neuromuscular transmission:

The aim of monitoring neuromuscular blockade (NMB) is to provide optimal paralysis during surgery and optimal recovery from paralysis by the end of anaesthesia. Neuromuscular monitoring techniques should aim to prevent morbidity and mortality from respiratory insufficiency. This is because muscle groups vary in their sensitivity to non-depolarizing blocking drugs (NDBD's), the extraocular muscles and those of the upper airway are the most susceptible; the small muscles of the hand and those of the abdominal wall are less susceptible, while the diaphragm is relatively resistant[36,37].

Conventially, it has been accepted that recovery from NMB is complete when adequate respiratory exchange with normal tidal volume is observed. However, the reliability of this observation has been questioned. Simple tests of adequate recovery following

reversal of NMB include the ability of the patient to open the eyes, to protrude the tongue, to cough vigorously and to sustain the head raised for 5 seconds with a vital capacity of 15-20 ml/kg. These tests are observed in an awake and cooperative patient which is not always the case.

The first method of measuring and recording NMB for clinical use in anaesthesia was electromyography (EMG) [38-40]. In this context, it records the compound action potential of the selected muscle in response to supramaximal stimulation of its nerve supply. The main problem with EMG is electromagnetic interference, but by gating and filtering techniques, clinically useful monitoring devices as the "Relaxograph" have been developed. At the present time, this device is especially useful for research or when the investigated muscles as the adductor muscles of the larynx or the facial muscles cannot be connected to the transducer.

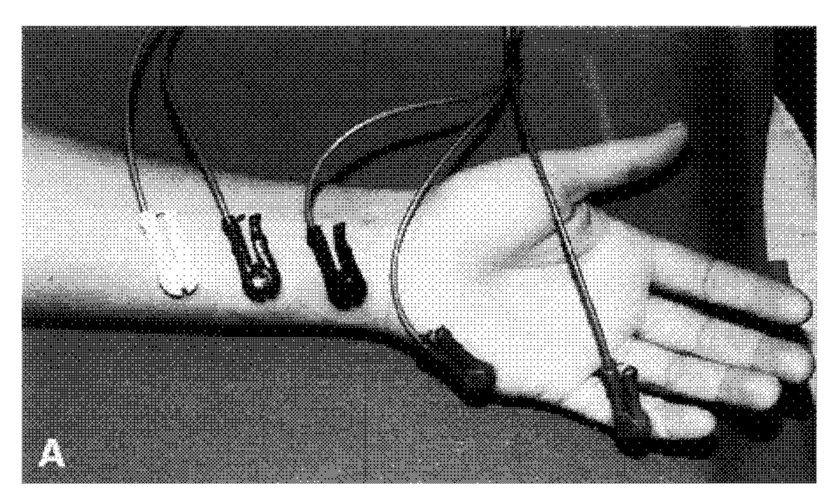


Figure 35: Electromyography electrodes.

The abductor digiti minimi is the muscle most frequently used for EMG. The suggested position for the recording electrode, is the ulnar aspect of the dominant hand, about one third of the distance between the distal carpal crease and the metacarpo-phalyngeal crease at the base of the little finger. The stimulating electrodes are placed on the volar aspect of the forearm over the ulnar nerve about 5 cm apart with the negative electrode distal. The ground or indifferent electrode is sited between the stimulating and recording electrodes (fig. 35).

The gold standard of measurement of neuromuscular response is recording the force of contraction evoked by supramaximal peripheral nerve stimulation in a selected muscle by mechano-myography (MMG). The "Myograph 2000" is probably the best known to measure the isometric contraction of the adductor pollicis muscle in response to stimulation of the ulnar nerve.

The train of four (TOF) stimulation pattern has become the most common method used for clinical assessment of NMB, in the present time, by using the nerve stimulator[41-43] (fig. 36).

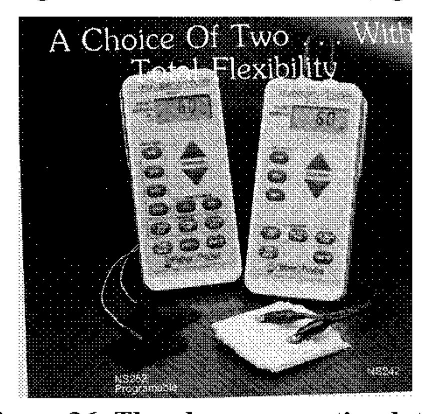


Figure 36: The ulnar nerve stimulator

By applying the electrodes along the ulnar border of the forearm, the anaesthetist, through ulnar nerve stimulation, can accurately monitor the depth of the block by assessing thumb adduction. Stimuli of 0.2 ms duration at 0.5 Hz are applied at 12 seconds intervals (fig. 37).

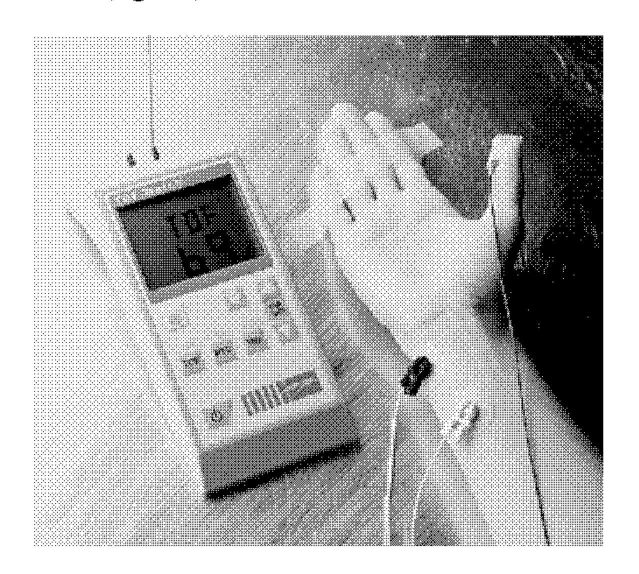


Figure 37: The ulnar nerve stimulator with the application of its electrodes.

By observed response, the nerve stimulator can elicit normal neuromuscular function. The TOF ratio compares the fourth amplitude response of the muscle to the first amplitude response. In the depolarizing NMB, the TOF pattern shows equal but reduced twitches with a ratio of unity. For competitive NMB, it shows progressively decreasing twitches in the 4 responses of the TOF. Reversal of block is complete when TOF ratio equals unity.

Reversal is incomplete with a ratio of 0.25 or 0.5. When there is no response to TOF stimulation, the block is considered irreversible.

Good recovery from competitive NMB is described at TOF ratio of 0.75, at which level the eyes are widely open, the tongue can be protruded and the head raised for 5 seconds. Here, coughing is vigorous and the vital capacity reaches 15ml/kg. With a TOF ratio of 0.6, negligible subjective and objective changes as diplopia and moderate facial weakness are observed, but without dyspnea[44]. Generally speaking, a TOF ratio of 0.75 with an ability to open the eyes widely, to protrude the tongue and to grasp the hand firmly for 5 seconds denote safe recovery of NMB.

Post-tetanic count, elicited by nerve stimulation, is used to assess intense blockade. Following 5 seconds tetanic stimulation at 50 Hz, the number of twitches produced by single pulses at 1Hz is counted[45]. Double burst stimulation (DBS) is used to assess recovery from NMB[46]. Two short tetanic stimuli of 50 Hz for 60 ms, are applied 750 ms apart. The second response is weaker than the first in NMB. It gives more sensitivity at detecting fade than the TOF (fig. 38).

The important advantage of the TOF pattern is that a pre-block control is not needed to assess the severity of NMB. The disadvantage is the difficulty of precisely estimating the TOF ratio in the absence of a recording device. It should be remembered that the basis of the safe use of NMBD's is the detailed knowledge of the pharmacology of these agents and their antagonists.

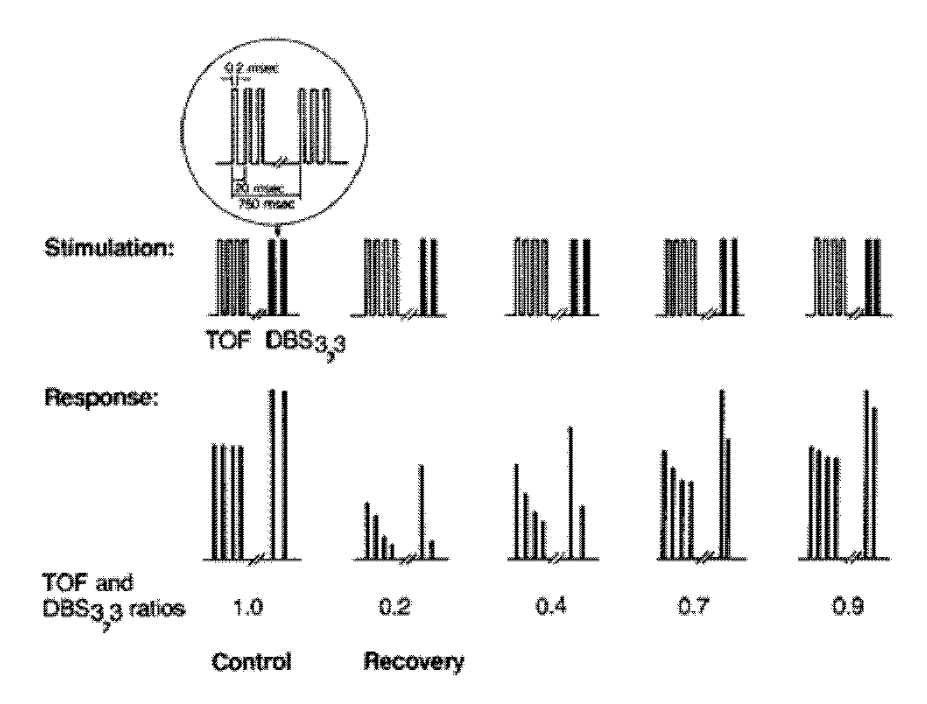


Figure 38: Pattern of electrical stimulation and evoked muscle responses to train-of-four (TOF) and double burst nerve stimulation (DBS $_{3,3}$) before injection of and during recovery from non-depolarizing neuromuscular blockade. TOF ratio = the amplitude of the fourth response divided by the amplitude of the first response. DBS $_{3,3}$ ratio = the amplitude of the second response to DBS $_{3,3}$ divided by the amplitude of the first response.

There is a significant incidence of residual NMB in the recovery room, even following routine reversal of the blockade. Reversal should be routine, unless absence of NMB is actively demonstrated. Adverse effects from persistent NMB are now well documented. Residual NMB can be reduced by the use of a nerve stimulator in the operating room and the use of intermediate acting

NMBD's, but the problem is not eliminated without the accurate measurement of the blockade. The use of long-acting non-depolarizing drugs results in increased incidence of residual paralysis. Even if accurate monitoring is used, long-acting NMBD's are more likely to result in delayed recovery at the end of anaesthesia than if intermediate-acting drugs are used. It would therefore be reasonable to question their use.

All patients who have been given NMBD's must be closely observed by trained personnel until they are conscious and have demonstrated adequate recovery from paralysis confirmed by a bed-side test such as the ability to sustain a five-second head-lift. A peripheral nerve stimulator should be available for susceptible patients as morbidly obese patients and those with significant lung or heart disease and those with neuromuscular, renal or liver disease. This is because postoperative respiratory failure from inadequate antagonism of residual NMB continues to be an important cause of anaesthetic morbidity and mortality.

Donati [47] holds the opinion that the proper use and interpretation of neuromuscular monitoring is a must. At the recent International Neuromuscular Meeting (Belfast, June 2001)[48], the recommendations for the universal use of nerve stimulators whenever NMBD's are administered was universally agreed and there was strong expressed preference for objective measurement of muscle relaxation to avoid postoperative residual block. As safety of anaesthesia improves, further gains will be incremental and the introduction of routine measurement of NMB offers an opportunity for reducing adverse events [48].

4.8. Monitoring anaesthetic depth

The "human monitors" play the main role in monitoring anaesthetic depth by clinical interpretation of signs of depth of general anaesthesia. Awareness during anaesthesia is simply prevented by little more anaesthetic than little less anaesthetic, guided by education and training. Electromyography, cerebral function monitoring and oesophageal tonometry are not definite monitors for anaesthetic depth. HRV has been discussed before as a promising monitor of anaesthetic depth. Recently, modified EEG as Bispectral Index (BIS) has been promisingly used to track adequate anaesthetic depth.

The BIS monitor is a multivariate index derived from the spontaneous EEG [49]. Variables derived from EEG that can measure the anaesthetic depth include BIS, SEF and MF. BIS is the bispectral index. SEF is the spectral edge frequency. MF is the median frequency.

BIS determines a linear component (phase) and a non-linear component (harmonic). It uses a space-lab monitor for a numeric zone and moving wave-form updated every two seconds. It is a unitless score of 0-100, where 100 means that the patient is awake and responsive, 70 means that free recall is lost and 60 means that consciousness is lost.

Spectral edge frequency (SEF) is the frequency at which 95% of the total EEG power lies below it and 5% above it. The median frequency (MF) is the frequency ranging between 0.5 and 30 Hz.

The calculation of BIS begins with sampled EEG that is filtered to exclude high and low frequency artefacts. A series of

algorithms next is performed to calculate BIS, and produce a simple number. (fig. 39)

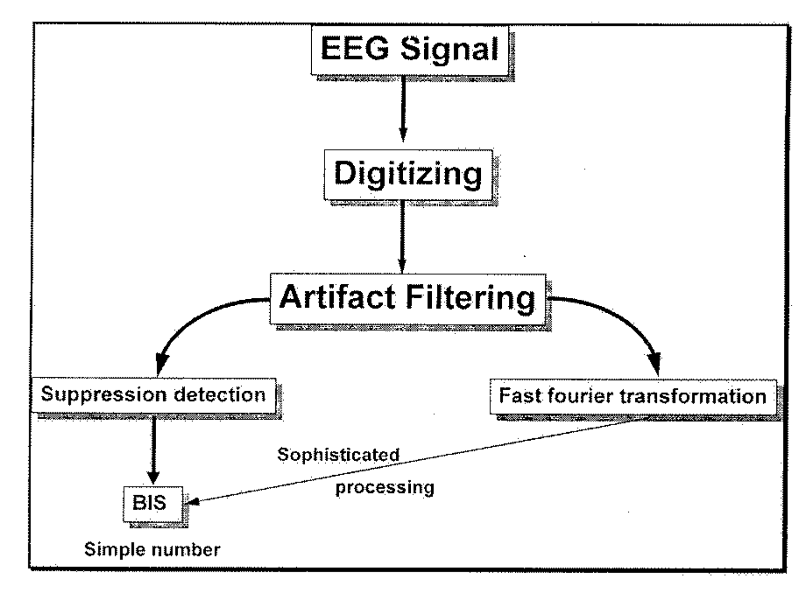


Figure 39: The calculation of the Bispectral Index (BIS)

For BIS, the percentage of time in the last 63 seconds in which the EEG signal is suppressed is called the Suppression Ratio (SR). This percentage ranges between 0% and 100%. Again the percentage of good epochs in the last 60 seconds that are used to calculate BIS and spectral values is called the Signal Quality Index (SQI). It ranges between 0% and 100%. It is not affected by the Suppression Ratio. The epoch is the time during which the BIS is calculated.

The electrodes or sensors of BIS are attached to three circles. The first is a forehead contact 4 cm above the nose. The second is a contact above the right or left orbit. The third is a contact on the

temple between the hair-line and the outer angle of the orbit (fig. 40).



Figure 40: The Bispectral Index electrodes

Monitoring with BIS has been reported to track hypnotic levels and to titrate intraoperative inhalation or iv anaesthetic concentrations. It allows more economic utilization of these agents and to reduce the time to wakefulness and extubation with promotion of faster theatre turnover. Below a BIS value of 60, there is a very low probability of patient recall. The range between 60 and 50 may denote deep sedation or light anaesthesia, and below 50, the patient is usually unconscious. Burrow et al [50] used levels between 60 and 50 to minimize the risk of awareness under general anaesthesia and kept the level between 70 and 60 for the last 15 minutes of the operation.

Gale et al [51] used BIS to measure anaesthetic depth using propofol for target controlled infusions. They concluded that the ideal BIS for general anaesthesia was defined as 50. At that level, target or manual control of propofol infusions showed similar anaesthetic depth and haemodynamic stability. They advised either method as suitable for maintenance of anaesthesia with propofol.

Intraoperative BIS monitoring can lead to improvement in the mean Aldrete Score for patient recovery with potential implications in patient safety and lower costs of service[52, 53].

In explicit memory (conscious or declarative), the patient can spontaneously and directly recall events happening under anaesthesia. Implicit memory (unconscious or non-declarative) is characterized by a change in task performance where the original stimulus cannot be directly remembered. However, both types of memory can be prevented by monitored adequate concentrations of inhalation or iv anaesthetics at all times. Unless necessitated by surgical requirements under muscle relaxation, it is preferred always to keep at least one twitch in a TOF. To prevent awareness, it is advisable to re-dose the anaesthetic induction agent during difficult intubations. A general useful rule is to reverse neuromuscular blockade before discontinuing N_2O as a prophylactic measure against awareness. Sometimes, particularly in circumstances where anaesthesia may be deliberately light (such as Cesarean section, trauma surgery and open-heart surgery), it is ethical to inform the patient preoperatively about the problem of awareness and to assure him/her by considering the prophylactic and therapeutic uses of amnesic agents [54, 55]. Generally speaking, the state of general

anaesthesia implies a lack of consciousness or awareness. Awareness can occur with or without conscious recollection of the events. For example, patients who are intubated yet open their eyes to command at the end of surgery are aware. Yet, frequently, they will not remember commands in the operating room, nor will they remember extubation. Thus, they may be aware without recall. The main challenge of the anaesthetist is to eliminate recall of unpleasant experiences during surgery.

However, it is to be emphasized that explicit recall of intraoperative events (diagnosed by recall and recognition tests) is but one measure of memory only and is not entirely reliable as a test of awareness. The unconscious storing of a traumatic memory (diagnosed by incidental test indicating learning and retention of previously presented words during anaesthesia) may act as a psychic irritant and pose the problem of post-traumatic stress disorder (nightmares, anxiety, depression, sanity, irritability … with changes in behaviour and/or performance) which may need subsequent psychotherapy. So, the addition of the BIS monitor to the armamentarium of modern monitoring may be useful in preventing awareness during general anaesthesia although this has not been totally validated.

4.9. Monitoring the brain and spinal cord functions:

In addition to awake testing and EEG monitoring including its BIS modification, modern development of electronics and microprocessors allows easy real-time monitoring of the nervous system functions by the anaesthetist, the intensivist or the critical care physician.

The brain has spontaneous electrical activity that can be monitored by the EEG. However, it can also respond to stimuli applied to peripheral or cranial nerves by evoked potentials (EPs). Examples are the somatosensory evoked potential (SSEP), the brain-stem auditory evoked response (BAER), the visual evoked response (VER) and the motor evoked potential (MEP). Such EPs may be monitored in the operating room to assess functions of the nervous system including the spinal cord.

The most widely used EPs in the operating room is the SSEP. In this technique, a peripheral nerve is stimulated with measurement of the neural response. Common sites of stimulation include the median nerve at the wrist, the peroneal nerve at the ankle and the trigeminal cranial nerve. It is currently thought that the incoming volley of neural activity from the upper extremity represents primarily the activity in the pathway of proprioception and vibration (the posterior column) and that the response from the lower extremity includes a contribution from the antero-lateral spinal cord (spino-thalamic-cerebellar pathways).

SSEP monitoring is indispensable during surgical procedures of peripheral nerves and plexus regions. The spinal cord

may suffer ischaemic injury during operations on the thoracic or abdominal aorta or even during angiography, where SSEP monitoring can provide safety. Perhaps the most common application of SSEP is monitoring during spinal corrective surgeries as scoliosis and spinal trauma. Recording SSEP from multiple electrodes placed directly on the cerebral cortex can be also used to locate areas during intracranial surgery. Again, during carotid endarterectomy, SSEP monitoring may guard against micro-embolization of the circle of Willis including the middle cerebral artery.

The SSEP technique has some limitations. One limitation is that the potentials enter the spinal cord via multiple nerve roots providing limited value in some surgeries. Another limitation is the sensitivity of the cortical responses to anaesthesia. As such, SSEP techniques are better used for stimulation recording from the spinal cord, being less susceptible to anaesthetic effects.

The BAER monitoring consists of a series of positive and negative waves that are recorded from the cortex by sound activating the cochlea of the ear or from the vertex and a non-cephalic reference. It has several applications needing monitored brain-stem activity during surgical procedures (fig. 41). It can be also used as a component of feed-back closed-loop control of general anaesthesia.

The visual evoked potentials **(VEP's)** are produced by light stimulation of the eyes and are recorded by electrodes placed over the occipital cortex. It is classically used in procedures near the

anterior visual pathways such as the pituitary gland to identify encroachment on the optic chiasma.

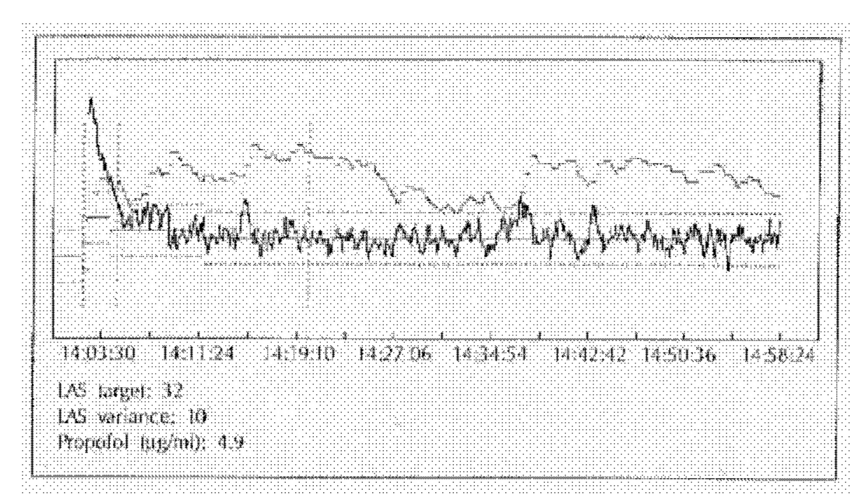


Figure 41: The brainstem auditory evoked potential response during total intravenous propofol anaesthesia

For **MEP recording**, the full length of central motor pathways can be monitored by stimulating the motor cortex transcranially either electrically or magnetically. The responses can be recorded in the spinal cord, the peripheral nerves or as evoked compound muscle action potentials. For stimulation of the spinal cord, electrodes are placed into the epidural or subarachnoid space. More experimental studies are needed before MEP monitoring becomes widely accepted.

The most common cranial nerve monitoring is used in posterior fossa surgery to preserve the facial nerve function and hearing. Several other cranial nerves can be monitored when needed. Most cranial nerves can be monitored for their motor

components, while the optic nerve can be monitored visually by the VEP.

The intracranial pressure (ICP) can be monitored by different techniques where devices are placed under local anaesthesia. A ventriculostomy with an intraventricular catheter remains the gold standard for ICP monitoring and management. A fiberoptic epidural ICP device (Camino catheter) can recently record wave-forms and record potentials from intracranial locations. An advantage is that in-vivo calibration is possible. All head-injured patients with Glasgow Coma Scale (GCS) less than 8 should have routine ICP monitoring. Patients under sedative or relaxant drug effects and those of GCS of 9-12 requiring major surgeries should be also monitored for improved outcome.

Cerebral blood flow (CBF) monitoring has recently been practically possible in the operating room and the ICU by using the transcranial Doppler (TCD) ultrasound method (fig. 42). It is a continuous non-invasive technique which uses sound waves to measure the velocity of the blood flowing in the basal arteries of the brain, specially the middle cerebral artery. Sound waves are transmitted through the relatively thin temporal bone. When they come in contact with the blood, they are reflected off the red blood cells back through the brain and skull to the detector. The velocity of the sound waves will be changed due to the motion of the red blood cells either toward or away from the detector. This phenomenon is known as the Doppler shift and is directly related to the velocity and flow direction of the blood cells. The flow velocity

will be directly related if the diameter of the artery and the measurement angle of the Doppler probe remain constant.

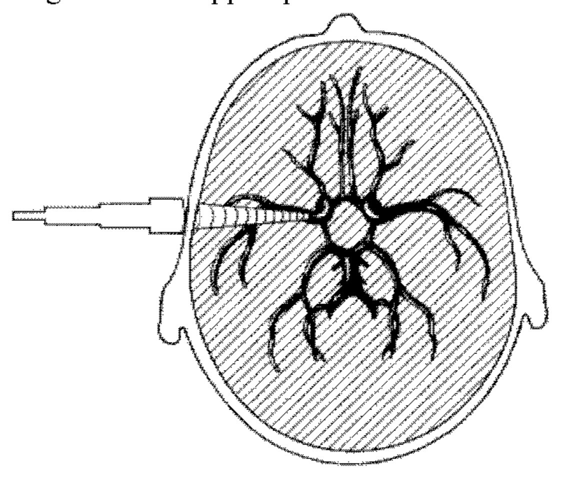


Figure 42: The transcranial Doppler ultrasound

TCD is used intraoperatively with carotid cross-clamping during carotid endarterectomy to measure relative changes in CPF and to diagnose microembolic stroke. It is also used during cardiopulmonary bypass (CPB) to detect microemboli and to estimate relative CBF changes. It has been used in the ICU to document the presence and severity of cerebral vasospasm during subarachnoid haemorrhage. TCD recordings may be helpful in evaluating patients with cerebral stroke, head injury and as a document for brain death.

Juglar venous bulb oxygen monitoring is useful for clinical assessment and management of global cerebral oxygenation based on monitoring arterial-juglar venous difference in oxyhaemoglobin content ($AVDO_2$) in patients with severe head injury.

The internal juglar vein (IJV) collects blood from the skull, brain and the superficial parts of the head and neck. It begins at the cranial base in the juglar foramen as a continuation of the sigmoid sinus. The sinus consists of a vertical segment and a short horizontal limb and drains in the juglar venous bulb (JVB) at the origin of the IJV. The IJV descends in the carotid sheath and then unites with the subclavian vein posterior to the sternal head of the clavicle to form the brachiocephalic vein.

The technique of JVB cannulation includes placing a catheter into the right IJV and advancing it in a retrograde way into the JVB. Caution must be exercised to avoid obstruction of cerebral venous flow that increases the ICP. This risk can also be minimized by using small-gauge catheters. The reliability of juglar venous oxygen saturation ($S_{Jv}O_2$) monitoring is increased by bilateral cannulation of the juglar bulbs.

By blood sampling from the JVB, the oxygen content of cerebral venous effluent can be measured and compared with that simultaneously measured in arterial blood by ABG analysis. $AVDO_2$ can be used as a reliable estimate of CBF together with cerebral arteriovenous difference of lactate (AVDL).

Monitoring of cerebral extraction of oxygen is defined as the arterio-juglar saturation difference and may provide a measurement of global cerebral oxygen metabolism than the $AVDO_2$ especially in the presence of anaemia in patients with traumatic brain injury (TBI). When oxygen extraction exceeds 60%, total oxygen delivery is inadequate compared with cerebral oxygen consumption. This information may be used to evaluate treatment designed to reduce

ICP and enhance oxygen delivery to meet cerebral metabolic demands.

Values of 60-75% for $S_{JV}O_2$ represent the normal range. Increased oxygen extraction in the form of 50-60% $S_{JV}O_2$ occurs in mild ischaemia. Moderate ischaemia associated with lactate production occurs at 45%-50% while severe ischaemia needing urgent treatment is the situation below 45% $S_{JV}O_2$. On the other side an increase in $S_{JV}O_2$ to a range of 75-90% represents relative or absolute hyperaemia, hypercapnea and A-V malformation. $S_{JV}O_2$ range of 90-100% denotes very low metabolic activity with brain death, profound hypothermia and A-V malformation.

The AVDL when divided by $AVDO_2$ yields the lactate oxygen index (LOI) which may be a reliable indicator of cerebral ischaemia in acute TBI.

Intraoperative monitoring of $S_{JV}O_2$ is feasible, practical and may be beneficial in patients undergoing neurosurgical procedures for detection and management of cerebral venous desaturation.

When increased ICP is caused by mass lesions, diffuse brain oedema or endotracheal suctioning, it is more commonly associated with a compromised CBF, identified by a decreased $S_{JV}O_2$and an increased cerebral oxygen extraction. So, in conjunction with routine monitoring of ICP in patients with severe head injury, monitoring of $S_{JV}O_2$ appears to be helpful in optimizing cerebral haemodynamics and may reflect the status of CBF. Continuous monitoring of $S_{JV}O_2$ by fiberoptic oximetry is now possible. Episodes of $S_{JV}O_2$ desaturation with a drop to less than 50% for more than 10 minutes are mostly due to cerebral or even systemic

effects as hypocarbia of hyperventilation or systemic hypotension respectively.

4.10. Echocardiography:

Echocardiography, depending on the characteristic of ultrasound, extends the role of the anaethestist for the diagnosis of cardiac anatomy and function status. The sound behaves according to the principle of longitudinally propagating waves with alternating compression and rarefaction of the transmitting medium and produces a sound energy. The normal range of sound that human-beings can perceive is 20-20000 Hz. A sound wave with a frequency more than 20000 Hz is called ultrasound[56].

The principal characteristic of ultrasound that forms the basis for its use in imaging by echo-cardiography, is its reflection from surfaces encountered in its pathway (Fig. 43). A surface is defined as the interface between two media of different acoustic impedence determined by the density and velocity of sound conduction through the individual material, and part of its energy is lost in this process. The degree of attenuation of ultrasound is proportional to its frequency[57]. This tends to limit the distance that ultrasound can penetrate before being completely absorbed. As the intensity of ultrasound decreases during its travel through the medium, the echocardiogram apparatus incorporates a mechanism to amplify echos from greater depth.

When an alternating current is applied to a piezo-electric element, it vibrates with production of ultrasound propagating in all directions. Vibrations in the backward direction are attenuated by a packing in the transducer of the echocardiogram. Through a thin

protecting layer, forward pulses are transmitted in the medium and sound pulses are converted to electrical signals. So, ultrasound creates its image by emitting high frequency pulses that travel through soft tissues. Various tissues possess different acoustic properties and each interface causes a small portion of the pulse energy to be reflected as an echo[58].

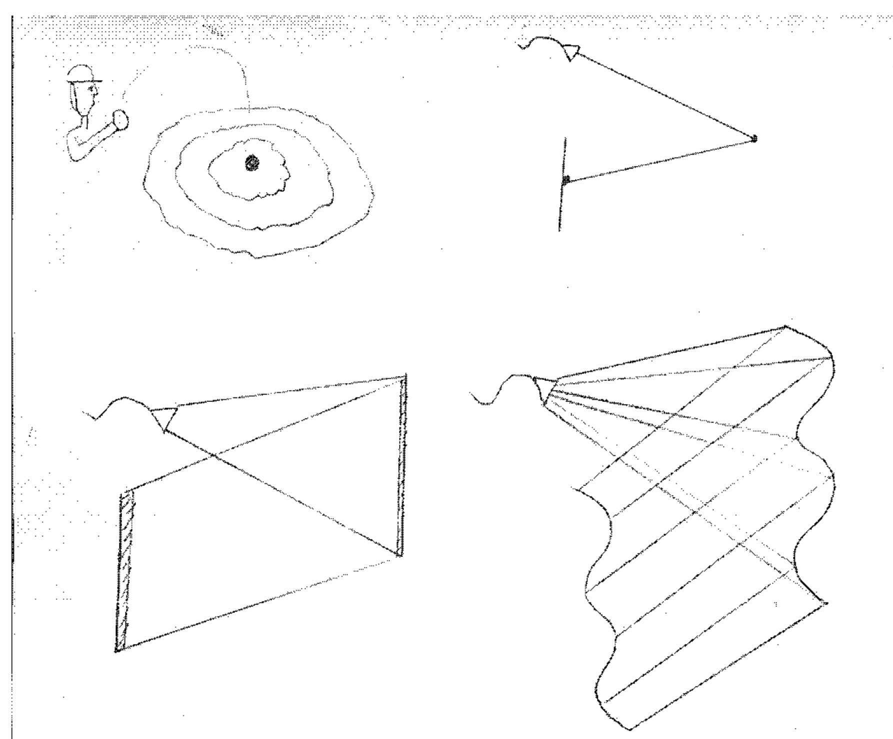


Figure 43: The idea of ultra-sound

As an imaging technology, ultrasound has significant advantages. Imaging can be repeated at frequent intervals on the same patient as an excellent and safe mean of monitoring. As blood is hypo-echogenic to the tissues, cardiac images show excellent

contrast at endocardial blood boundaries and valve structures. It permits visualization of virtually all portions of the myocardium at real time imaging rate as greater than three images per second. Doppler assessment of local blood velocities and coloured Doppler imaging permits accurate characterization of the direction and pattern of blood flow. Doppler may be continuous or pulsed. In continuous wave Doppler (CWD), two transducers are mounted together, one for transmission and one for reception. In pulsed wave Doppler (PWD) only one transducer is employed, which after transmitting a signal waits until it receives the returning echo before it fires again (fig. 44).

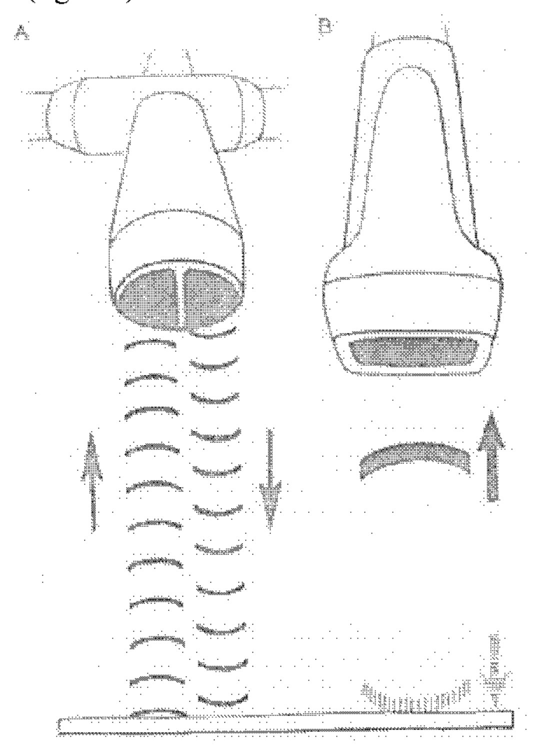


Figure 44 : Continuous (A) and Pulsed (B) Doppler.

In early echocardiography, the sound beam was focused in a fixed direction. The resulting display was called motion-mode (M-mode) or one-directional echocardiography with limited information[59]. In two-dimensional (2-D) echocardiography, the sound beam sweeps through an arc of 90° and shows the reflecting structures in the plane[57].

The M-mode is one dimensional but because the echo signal is displayed over time, it is really two dimensional. It allows precise measurements of changes in cavity size or wall thickness of the heart and a close look at wall motion as well as various anatomical structures including thrombi, vegetations and valvular leaflet excursions in real time. It is still used because it provides the highest resolution across a specific line. Although replaced by 2D real time imaging, with simultaneous 2D imaging, it became possible to know where the single line was cutting (fig. 45).

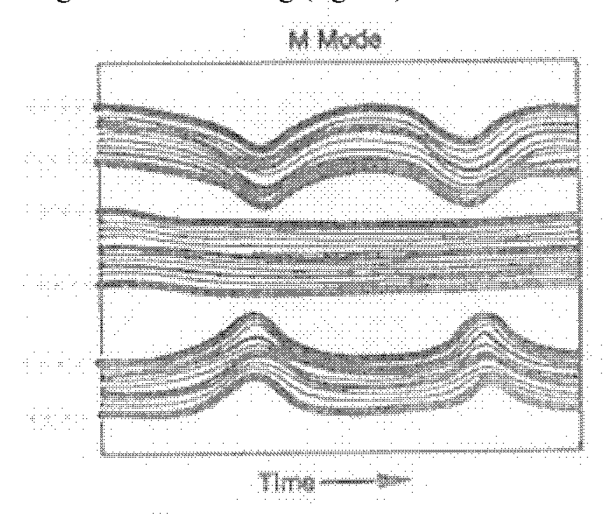


Figure 45: M-mode showing the sweep across the television screen or on recording paper.

At the present time, three-dimensional (3-D) echocardiography using a computer in still confined for research use[60]. In the PWD mode, the Doppler ultrasound provides information on pressure differences and blood flows in the heart and blood vessels[61].

Spectral Doppler

Blood flow velocity can be measured using pulsed wave (PW) or continuous wave (CW) Spectral Doppler [62]. The amplitude of the Spectral Doppler tracing is directly proportional to the measured red blood cell velocity. In CW Doppler two different transducers operate simultaneously. One transducer continuously transmits ultrasound signals while the other continuously listens to all returning signals. In PW Doppler, the same transducer listens and transmits. So, only the ultrasound signals returning from a specific depth along a line of interrogation will be analyzed. The disadvantage of CW Doppler is that the transducer cannot differentiate which signals come from which depth, so that the final analysis will represent an average of all ultrasound signals generated by moving red blood cells along the line of interrogation.

The Doppler shift is used to measure blood flow velocity. This, is turn, can be used to derive several variables useful in quantifying the severity of valvular heart disease. These include pressure gradients and flow velocity ratio across stenotic valves, valvular areas, and regurgitant fraction. Other important applications of Spectral Doppler include the measurement of cardiac output and the assessment of ventricular diastolic function[63].

Left ventricular (LV) diastolic dysfunction is achieved through PW Doppler measurements of diastolic blood flow velocity across the mitral valve and in the pulmonary venous system. This is important because diastolic dysfunction is now considered an important aspect of cardiac function. A non-compliant ventricle will result in higher central venous pressure (CVP) and pulmonary capillary wedge pressure (PCWP) for a given volume status. High filling pressures can be misinterpreted as volume overload which may lead to the initiation of inappropriate therapy. Diastolic dysfunction can also result in congestive heart failure even when systolic function is preserved. Ventricular compliance may change abruptly especially in patients with ischaemic heart disease and after coronary artery bypass surgery.

Colour flow Doppler represents a 2-D echo image with superimposed colour coding of the Doppler shift created by the moving red blood cells. In PW Doppler one pulsed signal is sent along a single line, while in Colour Doppler the transducer sends bursts of pulses. Unlike PW Doppler where the transducer waits for the returning signal before sending the next, in Colour Doppler the pulses are sent in succession along each line before the first one has returned. The amount of information that has to be processed is very considerable. Over 250,000 points are analyzed every second and must be colour coded depending on the direction and velocity of the returning signals[64]. By convention, blood flowing towards the transducer is coded red and blood flowing away from the transducer is coded blue. In Colour Doppler, high velocity blood flow is expressed in brighter colours, while darker colour shades are used to

represent the lower blood flow velocities. High velocity flow is usually displayed as a mosaic colour pattern, which is characteristic of the turbulent flows seen in shunts, fistulas, defects, valvular insufficiency and stenosis. The area of these abnormal flows can be measured, and in the case of valvular insufficiency, correlates well with the severity of the disease. A 2-D Colour Doppler can be also used to outline a poorly visualized lesion on 2-D echo as myxoma or thrombus. It is also useful to define the orifice diameter of an abnormal intracardiac communication as atrial septal defect (ASD).

Exact timing and measurement of an abnormal flow can be done by M-mode Colour Doppler as in hyperdynamic tachycardic patients. It is also very useful in the assessment of aortic dissection to document flow in the false lumen and to confirm the dynamic changes in the size of the false lumen with systole and diastole. Another use of Colour flow Doppler is to guide CW and PW Doppler measurements, where the Spectral Doppler is aligned in the area with the strongest colour signal. This enables the most accurate assessment of flow velocity and guides Spectral Doppler measurements.

The use of an oesophageal Doppler probe to measure cardiac output through a minimally invasive method was described in 1971[65]. The first commercial Doppler device within an oesophageal probe was reported in 1985[66]. Recently, the Hemo-Sonic cardiac output monitor has become commercially available for use in critically ill patients[67]. The Hemo-Sonic monitor comprises a 7mm diameter oesophageal probe incorporating both M-mode and pulsed Doppler ultrasound transducers. The cardiac output is determined

from a known correlation between aortic blood flow and cardiac output. The M-mode is used to measure the diameter of the descending aorta and the pulsed Doppler is used to measure the velocity of blood travelling down the descending aorta for each cardiac cycle. The monitor provides updated cardiac output values continuously once correctly sited in the oesophagus (Fig. 46).

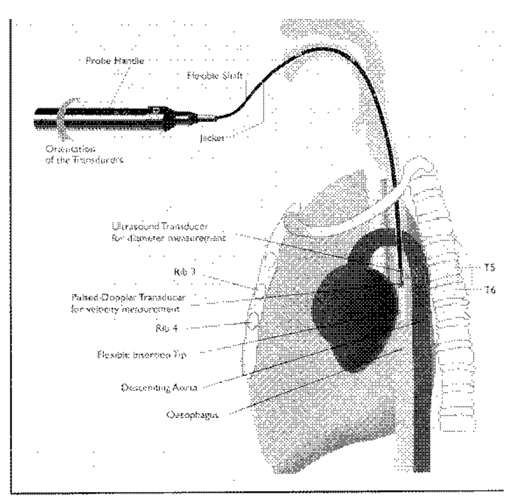


Figure 46: Correct placement of the Hemo-Sonic probe in the oesophagus

Moxon et al [67] evaluated the Hemo-Sonic monitor to determine cardiac output by means of M-mode and pulsed Doppler ultrasound. They compared cardiac output to paired measurements obtained by the standard thermodilution technique via pulmonary artery catheters in patients who had recently undergone cardiac surgery. The correlation between the two methods was very good with a correlation coefficient of 0.81, in agreement with previous published work[68]. However, there was a reduced correlation

between the two techniques at higher values of cardiac output. They concluded that the monitor has an application in patients where pulmonary artery catheterization is not desirable. The cost of the Hemo-Sonic monitor consumables is 200 to 300 dollars per application, comparable to the cost of placing and maintaining a pulmonary artery catheter. More research is needed to correlate cardiac output measurements by the Hemo-Sonic monitor and the transoesophageal echocardiography (TOE).

Transthoracic echocardiography:

For imaging techniques, the basic transthoracic examination includes the following views (fig. 47) through different windows [69]:

- Parasternal long axis view: The transducer is positioned at the third or fourth intercostal space just left to the sternum, with the patient in the left lateral decubitus position. The reference point of the transducer is positioned towards the patients' right shoulder. The image thus obtained represents a section through the long axis of the left ventricle. The image is oriented so that the aorta is displayed on the right, the cardiac apex to the left, the chest wall and the right ventricle anteriorly and the left ventricle and left atrial wall posteriorly.
- Parasternal short axis view: This view is obtained by rotating the transducer 90° from the long axis, so that the reference point is directed towards the patients' left shoulder. The right side of the heart including the tricuspid valve is displayed to the left and the pulmonary valve is displayed on the right side of the screen.

Inferiorly rotated, the transducer can show the papillary muscles and the left ventricle as a circular structure.

- Apical four-chamber view: This view can show all four chambers and also five chambers including the aorta can be displayed.
- Suprasternal notch view: The transducer is positioned in the suprasternal notch and the beam angulated inferiorly and slightly posteriorly. The ascending aorta is on the left and the descending aorta on the right. The origins of the right pulmonary artery and left atrium can be viewed.
- Subcostal view: The left and right atria and the interatrial septum can be visualized. It is possible to obtain a modified view of the left ventricle and the entire ventricular outflow tract.

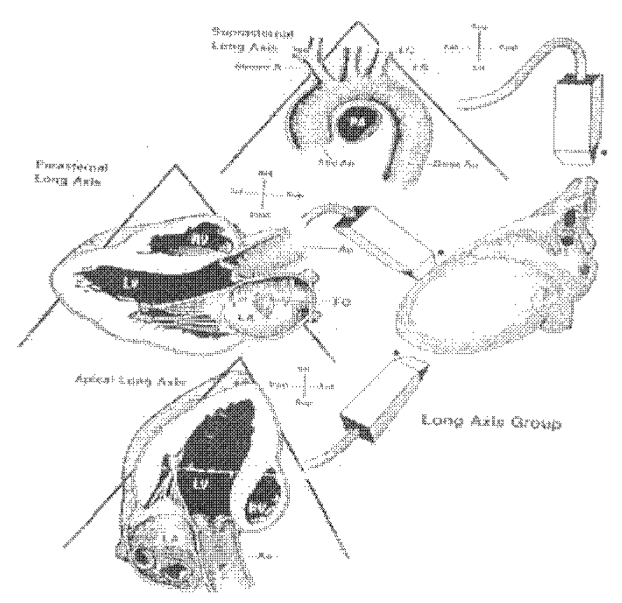


Figure 47 : Transthoracic echocardiography: parasternal long axis view and long axis planes obtained from the other imaging windows, the apical long axis and the suprasternal long axis.

The quality of image of transthoracic echocardiography may sometimes be unsatisfactory for various reasons as patient obesity, chronic obstructive pulmonary disease (COPD) chest wall changes with age and chest wall injury. Imaging from the chest wall requires the use of relatively low frequency transducers which provide poor resolution of cardiac structures. Moreover, prosthetic aortic and mitral valves present obstacles to the ultrasound beam transmission and result in acoustic shadowing. Transthoracic echo is also not suitable for intraoperative use if the surgeon and the anaesthetist compete for the working field and when ventilation is controlled.

Transoesophageal echocardiography:

Transoesophageal echocardiography (TOE) is a semi-invasive monitoring device that can be performed quickly with minimal risk[70]. It can provide important diagnostic information because chest wall interference and intrathoracic attenuation are eliminated. Furthermore, the close vicinity of the heart and thoracic aorta to the echocardiogram sensor allows the use of higher frequency and near focused transducers, which produce better resolution. In addition, some structures are better visualized by the transoesophageal approach, including wide areas of atrial chambers, left atrial appendage, prosthetic valves, left coronary arteries and the thoracic aorta. Because the ultrasound beam comes from the dorsal mediastinum, the lung tissue does not obstruct the ultrasound window to the heart. It has also the advantage that the surgeon and anaesthetist do not hinder each other in the working field. An

additional advantage is its ability to provide continuous stable views of the heart for protracted periods. In an intraoperative setting, it is an efficient monitor for the cardiovascular system compared to any intermittently applied diagnostic tool.

The basic structure:

The basic structure of all TOE probes is similar[71]. A commercially available gastroscope or bronchoscope is adapted by fitting a phased array transducer at its tip. The fiberoptics, together with the channels used for suction and biopsy are removed to provide space for the electronic connections of the transducer, but the guidance controls are retained, giving the tip at least 90° of forward and backward mobility and up to 70° of mobility in each lateral direction. The tip of the probe is 10-13 mm and the shaft is 9 mm in diameters (fig. 48). The length of the adult endoscope varies between 70 and 110 cm. The shaft is marked at distances of 10cm. A longer cable is desirable when the probe is used for intraoperative monitoring while the patient access is difficult. Some endoscopes are equipped with a thermocouple at the transducer tip to monitor temperature and prevent electric hazards. A recent development has been the modification of oesophageal probes so that they incorporate a series of electrodes which are suitable for atrial pacing.

The single plane TOE probe allows imaging from a single array mounted in the horizontal plane. The biplane TOE has two phased array transducers; one imaging in the transverse and one in the longitudinal plane[72]. The latest development is the varioplane or multiplane transducer. It is a mechanically rotatable single phased

array transducer which offers a large number of individual scanning planes through 180° arc[72].



Figure 48: Four tranoesophageal echo-cardiography probes are compared; from left to right: single plane, paediatric single plane, multiplane and biplane. Tips are viewed in relation to shafts at their maximum dimensions.

Standard adult sized TOE probes can be used in children weighing 20 kg or more. Smaller probes are used in children below this weight. A neonatal probe of 4mm tip diameter is used in very low weight infants[73].

For 2D imaging techniques, the basic TOE examination includes transgastric, lower, mid and upper transoesophageal and epivascular views through three windows, and all types of diagnostic images are possible.

Transgastric Imaging:

Starting with the probe in the stomach at 0° yields the classic short axis mid-papillary view. This view bisects the middle of the heart (the mid-left and right ventricles) and demonstrates the anterolateral and posteromedial papillary muscles (Fig. 49). This view has become synonymous with the assessment of left ventricular (LV) function since myocardial regions supplied by all three coronaries are visualized simultaneously. The right ventricle (RV) is seen as a crescentic structure on the left and its function should also be assessed. This view is also used to measure LV dimensions as well. Rotating the transducer to 90° demonstrates the anterior and inferior LV walls from the base to the apex. The true apex is not always visualized. Rotating further to 120° demonstrates the aortic outflow tract. Aortic outflow is almost parallel to the Doppler signal in this view which makes it useful for measuring flow velocities.

The transducer is rotated back to 0° and inserted deeper in the stomach. The tip of the probe is anteflexed as much as possible

to visualise the heart from the apex (Fig. 50). This view demonstrates the aortic outflow. Flow is almost parallel to the Doppler signal and this view provides another opportunity to measure aortic outflow velocities[71]. If the probe is rotated to the right, the right ventricular outflow tract (RVOT) can also be visualized. This view is useful in patients with congenital heart disease to assess the RVOT (e.g., presence of RVOT obstruction).

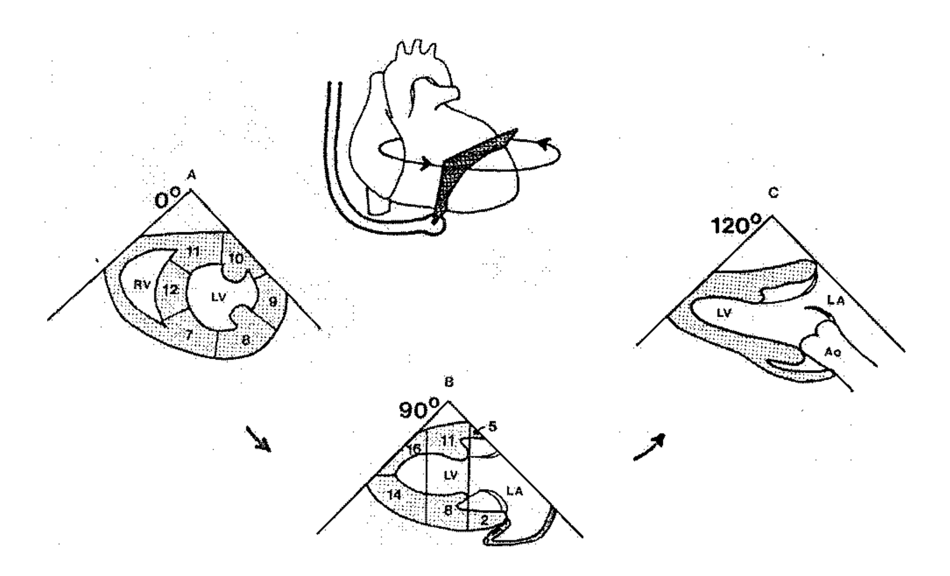


Figure 49: Transgastric imaging
(A) Transgastric mid-papillary view, (B) Transgastric two chamber view, (C) Transgastric longitudinal view. (Segments: 2= anterior; 7 = mid-anteroseptal; 8= mid-anterior; 9= mid-lateral; 10 = mid-posterior; 11= mid-inferior; 12= mid-septal; 14= apical anterior; 16= apical inferior) RV = right ventricle; LV = left ventricle; LA = left atrium; AO = aorta.

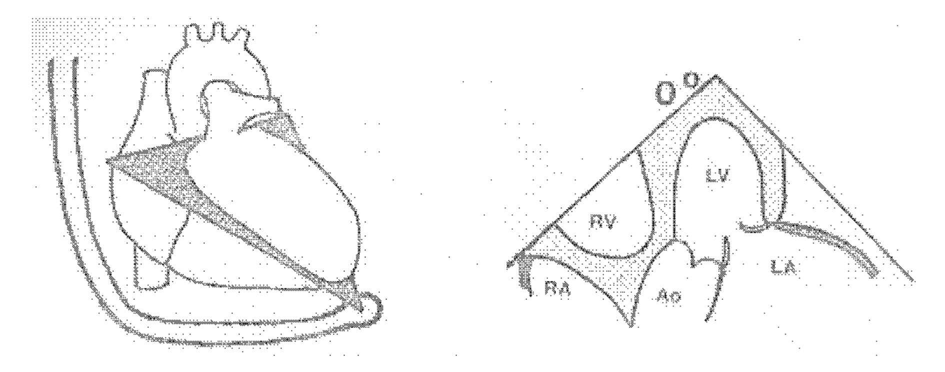


Figure 50 : Deep transgastric view.

Transoesophageal Imaging:

Withdrawing the probe to the lower oesophagus visualizes the mitral valve in short-axis. This image is useful for evaluating the aetiology and location of mitral valvular disease and is especially helpful during mitral valve repair. Further withdrawal of the probe to the mid- oesophageal level brings the right ventricular inflow and coronary sinus into view. If the probe is withdrawn a little more, a four chamber view is seen (fig. 51A). Both atriae and ventricles are visualized along with their valves. This view is useful for the assessment of ventricular function, valvular function and abnormalities of the atriae. Only the lateral and septal walls of the left ventricle are seen and the true apex is usually not well visualized. Excellent colour and spectral Doppler interrogation of the mitral and tricuspid valves can also be obtained.

Scanning the heart slowly in the four chamber view from 0° to 90°, provides additional information concerning ventricular function. At 90° a two chamber view enables the assessment of the

left atrial appendage and of the inferior and anterior LV walls (fig. 51B). This view also allows further assessment of the mitral valvular and subvalvular apparatus. Doppler assessment of left upper pulmonary venous and transmitral flow velocity is ideal in this view. Rotating the transducer to 130-150°, shows the aortic valve and proximal aorta (fig. 51C). This view can usually only be obtained with omniplane TOE and is most useful in the colour Doppler mode to evaluate the severity of aortic insufficiency. However, spectral Doppler assessment of flow velocity is inaccurate in this view because flow is not parallel to the Doppler signal. One must be cautious in evaluating wall motion in this view since the left ventricle may be foreshortened.

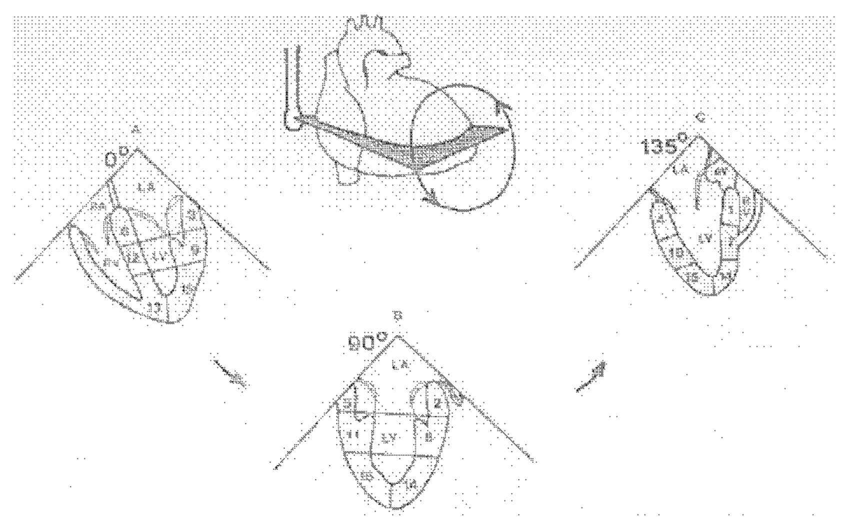


Figure 51: Transoesophageal imaging

(A) Mid-oesophageal four chamber view; (B) Mid-oesophageal two chamber view; (C) Mid-oesophageal long axis view. (Segments: 1 = anteroseptal; 2 = anterior; 3= lateral; 4= posterior; 5= inferior; 6= septal; 7= mid-anteroseptal; 8= mid-anterior; 9= mid-lateral; 10= mid-posterior; 11= mid-inferior; 12= mid-septal; 13= apical septal; 14= apical anterior; 15= apical lateral; 16= apical inferior). LA = left atrium; RA= right atrium; LV=left ventricle; RV=right ventricle; AV = aortic valve.

Slight withdrawal of the probe from the four chamber view in the mid-oesophagus displays the "five chamber" view which includes the aortic outflow tract (the fifth chamber). This view is useful for the assessment of aortic valve disease, abnormalities of the LV outflow tract (LVOT) and of the mitral valve. Rotation to 30-60° allows visualization of the "Mercedes Benz" configuration of the aortic valve. This is excellent for viewing the morphology of the valve (eg. bicuspid versus tricuspid). As the transducer is rotated to 90°, the aorta is unfolded. These views can also be used to assess the proximal ascending aorta.

The right side of the heart can then be seen by rotating the probe from the mid-oesophageal two chamber view towards the right (Fig. 52). This will visualize the right ventricular inflow and outflow tracts. Further rightward rotation brings the right atrium (RA), right atrial appendage and vena cavae into view. The interatrial septum and part of the left atrium (LA) can also be seen. This view can be helpful in identifying a patent foramen ovale and in defining types of atrial septal defects. The base of the heart is viewed from the upper oesophagus. The main pulmonary artery (PA) bifurcation is seen to the right of the aorta. This view is useful to assess aortic root size, the location of pulmonary artery catheters and abnormalities of the pulmonary arteries. Finally, the probe is turned towards the patient's back and the thoracic aorta is scanned first in the horizontal plane and then in the vertical plane. At 0° the descending aorta is circular until the arch is reached when it widens. At 90°, the descending aorta is tubular until the arch, at which point it becomes circular.

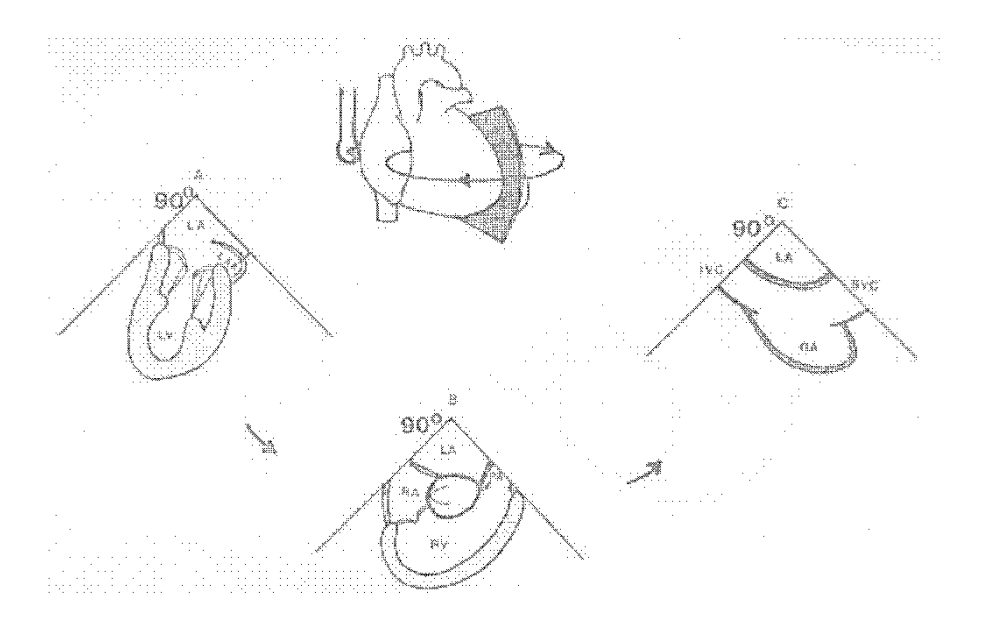


Figure 52: Transoesophageal imaging
(A) Mid-oesophageal two chamber view; (B) RV inflow and outflow view; (C) Mid-oesophageal longitudinal RA view.

This examination can generally be completed in 15 min. In cardiac surgical cases, a post-bypass examination needs not be as detailed. In general, ventricular function and volume are assessed as well as areas of the heart involved in repairs. It is generally agreed that an exception to the rule of performing a complete examination is when a patient's cardiac instability dictates brevity. In this case a quick look at the structures of interest may be the most practical approach.

Epivascular imaging:

Imaging of the ascending aorta for atherosclerotic disease is best achieved intraoperatively with epivascular echocardiography. This technique is predominantly used during cardiac surgery to obtain a detailed assessment of atherosclerotic disease in the ascending aorta and aortic arch prior to aortic cannulation. Embolisation of aortic plaque(s) is probably the most important aetiological factor in the development of perioperative strokes in these patients[74]. If aortic atherosclerotic disease can be identified then alterations in surgical technique may decrease the rate of neurological complications[74].

Epivascular echocardiography is important because detection of atherosclerotic disease by surgical palpation is accurate in only 50% of cases. Moreover, with TOE, a small portion of the ascending aorta is obscured by the trachea and left main bronchus. Unfortunately, this is a major site of surgical manipulation (aortic cannulation and clamping). Any suspicion of severe disease should be verified with epivascular echocardiography which is the current intraoperative gold standard in imaging of the ascending aorta. The epivascular examination is usually performed by the surgeon. A sterile-wrapped transducer is positioned directly over the aorta before aortic cannulation. The assessment usually starts at the aortic valve and the transducer is slowly moved distally towards the innominate artery. It is important to have a centered circle and not an oblong image of the aorta; this confirms that the transducer is perpendicular to the axis of the aorta. A second assessment can be done with the transducer parallel to the ascending aorta. The

posterior wall is well demonstrated with the probe directly over the aorta. To visualize the anterior wall of the aorta where most of the surgical manipulation will occur, it is necessary to improve the near field image. This can be achieved by positioning the probe over a water or gel filled glove which is applied to the area being scanned. Alternatively the field can be flooded with warm saline.

Technique of TOE:

The patient history of the disease should be taken. The patient should stop oral intake for 6 hours before the procedure. History of any dysphagia or oesophageal disease should be elicited. Dentures and oral prostheses are removed and an iv line is placed. Lidocaine spray and viscous lidocaine lubricants are used to suppress the gag reflex even in the intubated patient. Conscious sedation is provided by an iv midazolam dose of 0.05mg/kg. An anticholinergic agent may be needed to suppress salivation and decrease secretions. The patient lies in the left lateral decubitus position and the probe is introduced through a bite guard till the posterior pharynx and the awake patient is asked to swallow to direct the probe to the upper part of the oesophagus to approximately 25 cm distance. In the anaesthetised intubated patient, the technique is easier. Following the procedure the patient must be observed till recovery from sedation and food is withheld for 1-2 hours till the effect of the pharyngeal local anaesthetic has resolved.

The TOE is contraindicated with the presence of oesophageal pathology, gastric ulcerations or gastrectomy, cervical disc disease,

infections, coagulation disorders and liver disease. Complications include technique failure; pharyngeal, oesophageal or upper gastro-intestinal tract (GIT) bleeding; laryngospasm or aspiration; arrhythmias; transient vocal cord paralysis and untoward effects of iv sedation.

Indications of TOE:

In April 1996, guidelines of the perioperative use of TOE were published by the American Society of Anaesthesiologists and the Society of Cardiovascular Anaesthesiologists based on retrospective evidence and expert opinion and four specific categories of indications were defined. However, the most important indications included:

1. Assessment of regional cardiac function and detection of myocardial ischaemia:

   The relation between segmental wall motion abnormalities (SWMA) and myocardial perfusion makes TOE a sensitive monitor for detecting myocardial ischaemia. A decrease in systolic wall motion occurs within seconds after cessation of coronary blood flow and its extent relates to the severity of coronary insufficiency to the affected area. Akinesia implies more severe coronary insufficiency while dyskinesia suggests transmural ischaemia or infarction.

2. Assessment of global cardiac function and measurement of cardiac output:

   Qualitative assessment of global ventricular function is achieved through visual inspection of wall motion. The echo-cardiographer inspects a particular view and characterizes

function on subjective assessment with the ability to analyse images rapidly on-line which is useful for the unstable patient. During quantitative assessment, cardiac chamber dimensions at systole and diastole are measured. Accurate measurements of the preload as left ventricular end-diastolic volume (LVEDV) is important in evaluating global systolic function. Ejection fraction (EF), stroke volume (SV) and cardiac output (CO) are then calculated. EF equals end-diastolic to end-systolic volume difference related to end-diastolic volume. End-diastolic to end-systolic area difference related to end-diastolic area reflects fractional area change (FAC) denoting global left ventricular function.

Cardiac output (CO) can be determined by M-mode and 2-D TOE. Linear or area measurements are converted to volumes and CO is delivered through the product of heart rate and stroke volume. The determination of stroke volume by Doppler echocardiography is based on the measurement of blood flow velocities across cardiac valves or in the aortic root which is nearly circular and changes minimally during ventricular ejection. After-load is equivalent to end-systolic wall stress and can be determined by end-systolic wall thickness and peak systolic pressure.

3. Assessment of cardiac anatomy and blood flow pattern: Echocardiographic assessment of heart valve diseases requires a combination of M-mode, 2-D and Doppler techniques. For patients requiring valve surgery, because of the potential for suboptimal results, it is preferable to recognise the success of

surgery in the operating room rather than waiting for postoperative complications to develop that necessitate a second operation. This unique ability during valve surgery gives TOE the ego of widespread application for this purpose.

4. Assessment of congenital heart disease and efficiency of repair: For diagnosis of congenital heart diseases, TOE in paediatrics is applicable to infants as small as 2400 g, due to smaller biplane paediatric probes and recent imaging techniques. During surgical repair of congenital anomalies, it offers the advantage of uninterrupted operation, decreased potential violation of the sterile field and continuous haemodynamic evaluation[75,76].
5. Detection of intracardiac air or thrombus:
   Air bubbles or thrombi in cardiac chambers can be visualized by TOE and this is of important diagnostic value both for urgent management of the trapped air or for prophylaxis of embolic complications of cardiac thrombi[58].
6. Diagnosis of pericardial disease:
   TOE is the technique of choice for diagnosing even small pericardial effusions[69]. At the ICU, it evaluates patients with suspected cardiac temponade and TOE may be used at the bedside to guide pericardiocentesis. However, pericardial effusion has to be clinically differentiated from constrictive pericarditis.
7. Diagnosis of aortic aneurysm and dissection:
   For diagnosing aortic aneurysm and aortic dissection, TOE can provide useful information as the presence and location of an aortic thrombus together with the extension of the abnormal wall

thickness. It has the advantage over aortography of providing optimal bedside screening without the use of iv contrast agent in those patients who may have compromised renal function. In addition, complications as haemothorax or associated myocardial ischaemia are diagnosed.

8. Guiding intra-aortic balloon pumping:
   TOE has valuable guiding roles to play before, during and after insertion of an intra-aortic balloon pump. It has other roles to play before and during pumping, while during weaning, it can be used to study left ventricular function[64].

In spite of the valuable role played by TOE for diagnosis and during cardiac surgical repair, its role during general anaesthesia is limited. Hazardous problems of general anaesthesia for the cardiac patient are expected to take place during laryngoscopy and endotracheal intubation. Serious cardiovascular responses cannot be assessed by TOE because the probe is practically introduced in the oesophagus with imaging only after and not before endotracheal intubaiton. Then, the anaesthetist is left with the echo changes during maintenance of anaesthesia which can be detected by other monitors devoid of the need of the equipment or the need for expert interpretation of echocardiography in the operating room. However, the value of preoperative patient assessment by echocardiography is a fundamental addition to the anaesthetist.

4.11. Thromboelastography:

Normal haemostasis is defined as the controlled activation of clot formation and clot lysis that stops haemorrhage without permitting inappropriate thrombosis. This means that haemostasis is the net result of the two systems working together; the coagulation system that produces the clot and the fibrinolytic system that dissolves the clot. When the balance between these two systems shifts towards procoagulation, the result is thrombosis and when the balance shifts towards fibrinolysis, the result is haemorrhage. So, it is logic to consider that a coagulation test that does not measure the net result of both the coagulation and fibrinolytic systems, would fail to properly analyze patient haemostasis.

Ignoring the interactive nature of haemostasis by analyzing separate blood components as platelets, fibrinogen level and coagulation factors, may result in artifacts that do not match the clinical condition. Also, measuring single factors quantitatively can be misleading because the quantity as measured by an assay, does not reflect the actual functional activity, which depends on the presence, and activity of activators, inhibitors and cellular elements.

The current view of intrinsic, extrinsic and common coagulation systems describes coagulation mechanisms with one enzyme working after another with some mechanisms of feedback amplification and inhibition derived in the plasma medium. This view has been criticized, being not applicable to the low shear environment of the sluggish venous flow. The current concept has been recently accused by inaccuracy and oversimplification and is replaced by a theory of enzyme complexes existing on the surfaces

of cells, passing one another their substances until the final product, fibrin, is formed[77]. The cell surfaces of importance are those of the platelets, which are activated and adhere to the site of the injury. They localize the clotting process, enhance their activities, and protect the enzyme complexes from inhibition that circulate to protect against the propagation of the clotting activation downstream. This surface theory provides an explanation of how some individuals with low concentration of coagulation factors can maintain haemostasis, while these same individuals will bleed if their platelet function is compromised. Once the importance of the platelet surfaces and their interactions with the coagulation process are understood, the value of prothrombin time (PT) and activated partial thromboplastin time (aPTT) as substitutes for platelet surfaces' interactions is questioned. Coagulation factor deficiencies may not be evident in terms of abnormal PT and aPTT values until they are more than 50% reduced. Again, hypercoagulability is difficult to detect on standard coagulation tests unless the platelet count or fibrinogen concentration is markedly increased. In a patient with fibrinolysis secondary to hypercoagulability, D-dimer and fibrin degradation products (FDP) tests would show high fibrinolytic activity, while PT and aPTT results would be normal[78]. In such a situation, antifibrinolytic drugs might be prescribed, shutting off the fibrinolytic system, producing more imbalance toward procoagulability and may result in stroke or acute myocardial infarction.

Thromboelastograph (TEG) coagulation analysis provides a method for evaluation of the whole coagulation system from initial

clot formation to clot retraction or dissolution[79]. It monitors the thrombodynamic properties of the blood as it is induced to clot under a low shear environment resembling sluggish venous flow. The overall coagulation profile of the blood sample can be quantitatively or qualitatively interpreted in terms of normal, hypo- or hypercoagulable state and the degree of lysis. The TEG can also guide therapy in the form of fresh frozen plasma (FFP), cryoprecipitate, platelets or antifibrinolytic drugs. In addition, these therapies can first be applied in vitro to confirm their effects on the patient blood sample before administration of treatment. In addition to the "inactivated" TEG, activation reagents shorten the result time and improve precision and can allow differential diagnosis.

The TEG instrument consists of a sample cylindrical cup or cuvette and a measurement pin or piston, which is attached to a calibrated torsion wire[80] (fig. 53, 54).

A small sample of blood (0.36 ml) is placed in the cup and allowed to clot as the cup oscillates through an angle of 45^{o}. Each rotation cycle lasts 10 seconds. The elastic shear modulus of the sample is measured as fibers composed of fibrin and platelets are formed and attach the cup to the pin, which becomes monitored for motion. The strength and rate of these fibrin-platelet bonds affect the magnitude of the pin motion such that strong clots move the pin directly in phase with the cup motion. Thus, the magnitude of the output is directly related to the strength of the formed clot. As the clot retracts or lyses, these bonds are broken and the transfer of cup motion is diminished. The rotation movement of the pin is converted by a mechanical signal that can be monitored by a

computer. The resulting haemostasis profile is a measure of the time it takes for the first fibrin standard to be formed, the kinetics of clot formation, its strength and dissolution.

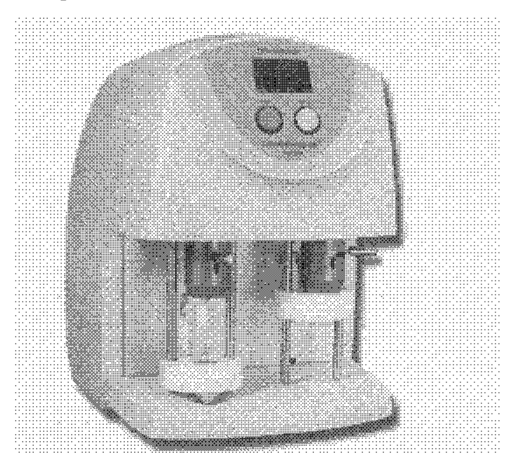


Figure 53 :The Thromboelastograph instrument.

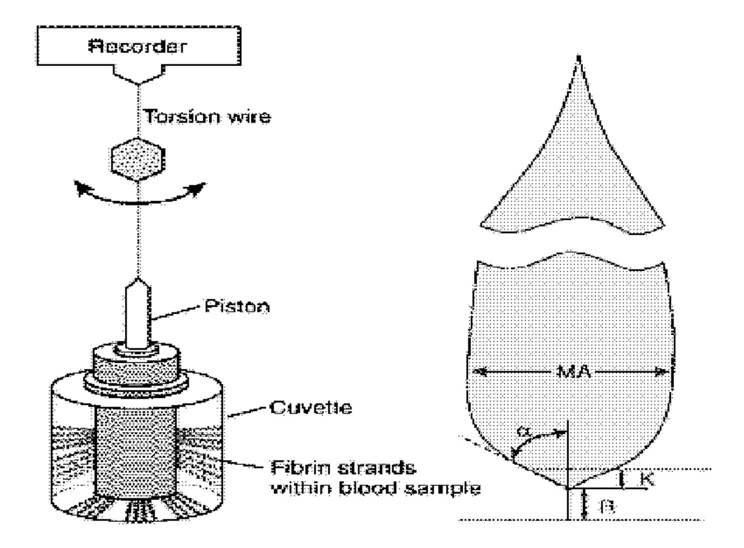


Figure 54 : The Thromboelastograph and its principle.

To evaluate the graphic information displayed by the TEG system, five main quantitative parameters of clot formation and lysis are measured[80] (Fig. 53). R is the reaction time which represents the period from placing the blood sample in the cup until the initial fibrin formation (normal range = 19-28mm). K is the coagulation time which measures the speed to reach a certain level of blood clot strength (normal range = 8-13 mm). Alpha (α) is the clot formation rate or clot strengthening which measures the rapidity of fibrin build-up and cross-linking (normal range of α angle= 29^{o}-43^{o}). MA or the maximum amplitude represents the maximum clot strength and is a direct function of the maximum dynamic properties of fibrin and platelet bonding. So, it is a direct function of fibrinogen concentration, platelet count and quality and the interaction of fibrin and the platelet plug (normal range=48-60mm). The fibrinolytic index for non-computerized TEG is whole blood clot lysis index (WBCLI, normal>85%), which is the amplitude 60 minutes after the MA as a percentage of MA and represents the amount of clot retraction or lysis (LY). Computerized TEG reports LY30 and LY60 (%) as fibrinolytic indices. These measure the reduction in the area under the TEG tracing from the time MA until 30 (LY30, normal<7.5%) or 60 (LY60, normal < 15%) minutes after the MA[81].

The R value or the reaction time is normally 7.5-15 min. It is considered comparable to the whole blood clotting time and may be accelerated by adding celite to the TEG sample in the cuvette. The R value is prolonged by a deficiency of one or more plasma coagulation factors. The K and alpha angle values may be prolonged

by any factor slowing clot generation such as plasma coagulation factor deficiency or heparin anticoagulation. The MA value may be decreased by either qualitative or quantitative platelet dysfunction or decreased fibrinogen concentration. (Fig. 55) shows qualitative interpretation of characteristic TEG abnormalities of clot formation and fibrinolysis[80].

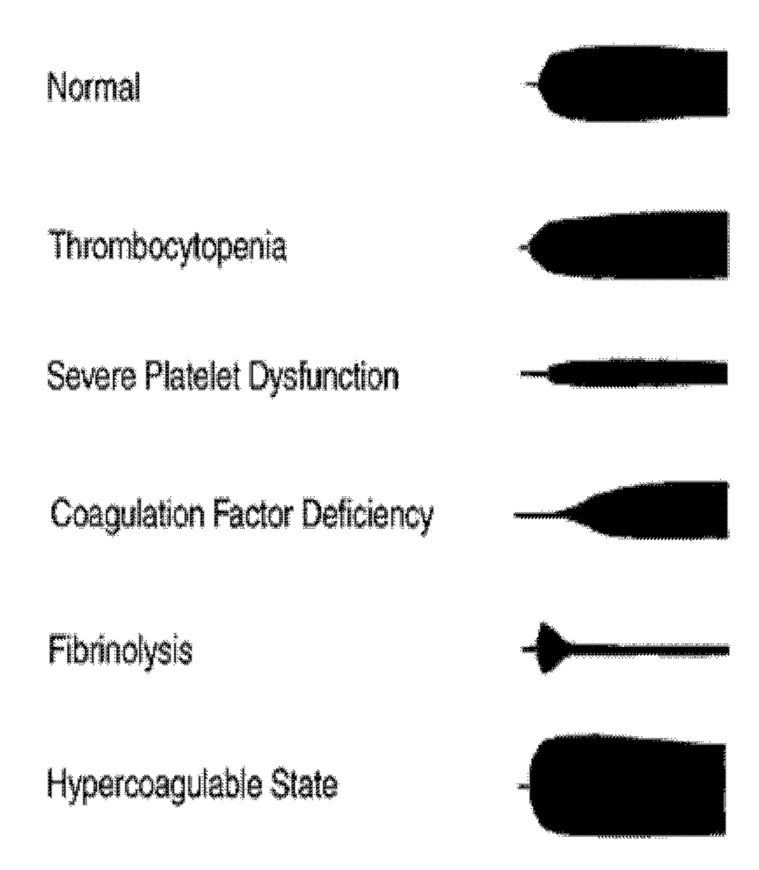


Figure 55 : Characteristic Thromboelastograph tracings.

The Sonoclot is an alternative to TEG for measuring viscoelastic coagulation of blood. Compared to TEG, it immerses a rapidly vibrating probe into a 0.4 ml sample of blood. As clot formation occurs, impedance to probe movement through the blood increases and generates an altered electrical signal and characteristic clot "signature". The Sonoclot may be used to derive the activated clotting time (ACT) as well as to provide information regarding clot strength and clot lysis[81].

Both TEG and Sonoclot generate characteristic diagrams by translating the mechanical resistance encountered by the sensor as it moves through the clotting blood sample. Measurements derived from these diagrams have been related to more traditional measures of coagulation such as the ACT[82]. Abnormal patterns have been associated with coagulation factor deficiencies and functional platelet abnormalities. TEG analysis is very sensitive in the identification and measurement of hypercoagulability, which is not detected by routine laboratory tests[83]. One of the more common applications of TEG analyzer is the real-time detection of excessive fibrinolysis during liver transplantation[84] or after orthopaedic surgery[85]. It can also differentiate bleeding from coagulopathy after cardiopulmonary bypass[86]. Transfustion can be reduced in complex cardiac surgery when guided by TEG[86]. Recent computerization and automation of these instruments have improved the reproducibility of the measurements and have made the results more accurate.

Recently, an improved TEG method which is less sensitive to some handling issues associated with the technique, has been introduced (fig. 56). This new method, named rotation

thromboelastography (ROTEG) is based on an optical detection of the movement of a disposable plastic sensor attached to a short axis guided by a ball bearing, which is inserted into the clotting blood and the axis is connected with a torsion wire (fig. 57). The ROTEG technique has been simplified so far that the test can also be performed at the bedside[87].

ROTEG tests include ExTEG, InTEG, FibTEG, ApTEG and Hep TEG for normal values for each of them. Rapid overview and differential analysis is achieved within 10 minutes with each ROTEG analysis. ExTEG denotes extrinsic activation by tissue factor reagent for fast assessment of whole blood coagulation. InTEG provides intrinsic activation by contact activator reagent for assessment of clot formation and intrinsic coagulation pathway with strong heparine influence. FibTEG entails ExTEG and fibrinogen receptor antagonist for specific registration of fibrinogen status. ApTEG denotes ExTEG and aprotinin for in-vitro fibrinolysis inhibition. Lastly HepTEG tests InTEG and heparine inactivation by heparinase.

Both TEG and ROTEG methods are sensitive for a variety of platelet function disorders, best primarily for deficiencies of coagulation factors, thrombocytopenia, the presence of hypercoagulants and also for the detection of hyperfibrinolytic stages. In contrast to coagulation tests, TEG is also partly sensitive for factor XIII activity [87]. The reaction curves of TEG and ROTEG are as typical as an ECG with rumerical data on clot kinetics and stability.

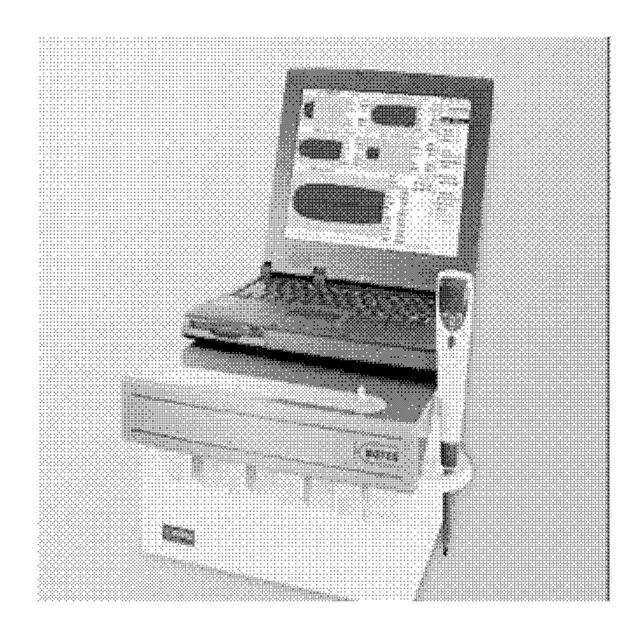


Figure 56: The Rotation Thromboelastograph instrument

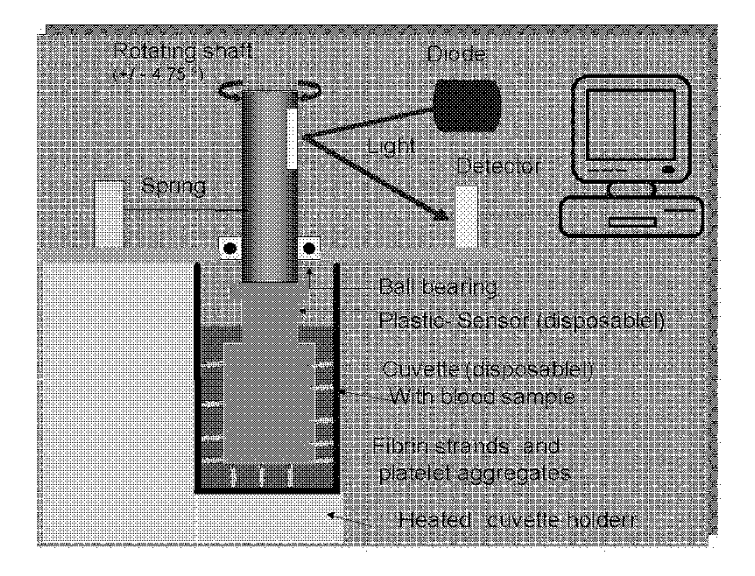


Figure 57: The principle of Rotation Thromboelastography

4.12. The central venous and pulmonary artery catheters:

Indices of both right and left ventricular filling pressures are monitored by the rates at which intravascular fluid and/or blood should be infused. For this purpose, central venous and pulmonary artery catheters are placed in specific patients by experienced personnel to minimize the risk of complications.

4.12.1. The central venous catheter:

Measurements of the central venous pressure (CVP) are useful in fluid management of patients without significant cardiovascular disease and those suffering from major trauma or undergoing prolonged surgeries with significant blood loss. A long catheter is passed into the superior vena cava via the basilic vein from the cubital fossa or a shorter catheter is passed via the internal jugular or subclavian veins by percutaneous Seldinger technique (fig. 58). Chest x ray is recommended after successful or failed catheterization for assuring correct positioning and excluding pneumothorax. Measurements are usually made using a simple fluid manometer or the catheter may be attached to a transducer where values are displayed on a screen after zeroing and calibration. The CVP is usually measured with the patient lying flat and is expressed in cm H_2O above a point in level with the right atrium, e.g. mid-axillary line, and its normal range is 3-10 cm H_2O.

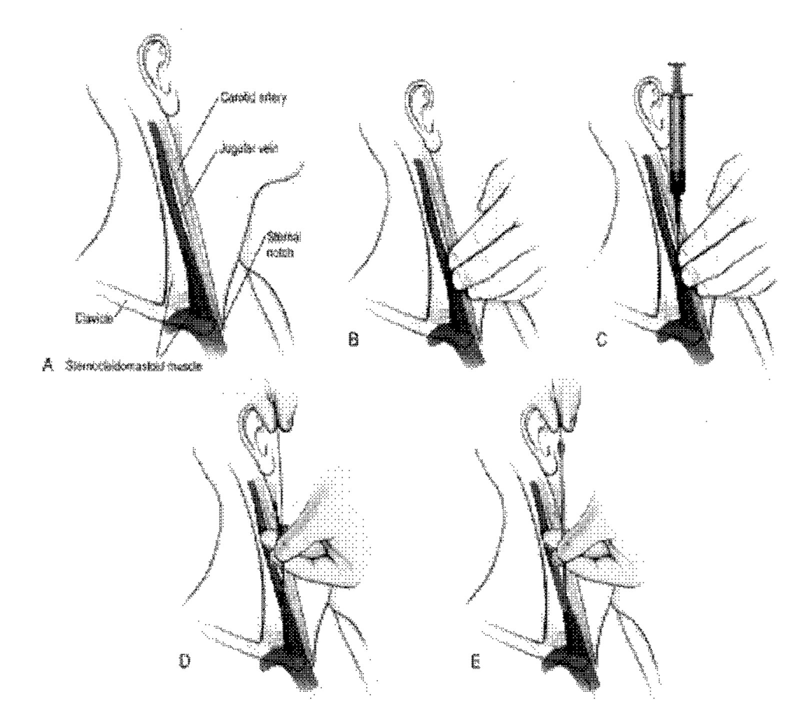


Figure 58: Central venous cannulation

The venous wave-form can be seen as a displayed pressure tracing. CVP monitoring is useful in indicating right ventricular preload and cardiac function. A saline volume challenge of 200 ml given over 5-10 minutes causing a rise of CVP of 2-5 cmH_2O may suggest hypovolaemia in a patient with good ventricular function. Monitoring of CVP is also useful for estimating haemorrhage, and to verify the adequacy of volume replacement during major surgeries.

It is now recognized that the right atrial filling pressure, measured by the central venous catheter, does not reflect left filling atrial pressure in patients with compromised right or left ventricular function.

Central venous line insertion requires a certain level of experience and may be associated with significant complications, related both to the procedure of catheter insertion (pneumothorax, haemothorax) or to the presence of an indwelling venous catheter in the circulation (air or catheter embolization, venous thrombosis, cardiac arrhythmias, sepsis).

Measuring CVP through a peripherally inserted venous cannula might be an alternative to central venous line insertion. This has not been widely advocated because peripheral veins have valves that may interrupt the continuous column of blood between the right atrium and the peripheral vein. Peripheral veins are also thin-walled and may be more easily subjected to compression and occlusion by the surrounding soft tissues. However, in both animals and humans a correlation between CVP and peripheral venous pressure has been reported, though the latter tends to be higher than the former due to the additional hydrostatic effect of the blood column between the central and peripheral veins. Some studies suggested that fluid resuscitation produces parallel changes in central and peripheral venous pressures [88,89]. Recently, Charalambous et al [90] placed peripheral venous catheters 14-20 gauge in the distal forearm or wrist areas. They recommended further studies to determine whether the exact catheter size or site of insertion influences peripheral venous pressure values and the difference between central and peripheral pressures, especially at the emergency department. They suggested that peripheral venous pressure measurements give little information about the absolute CVP values or the values of CVP changes. However, they concluded that the

direction of the changes of peripheral CVP might have a role in guiding fluid therapy.

A displayed normal CVP waveform through a central venous catheter, shows a pattern of three upstrokes and two descents that correspond to certain events in the cardiac cycle (fig. 59).

The "a" wave represents the increase in atrial pressure which occurs during atrial contraction. The "x" descent is the decrease in atrial pressure as the atrium begins to relax. The "c" wave occurs before total relaxation is completed, and is caused by the bulging of the tricuspid valve into the atrium during the early phase of right ventricular contraction. The "x" descent following the "c" wave is a continuation of the primary "x" descent and is caused by a drop in pressure brought about by a downward movement of the ventricle and tricuspid valve during the later stage of ventricular contraction. The "v" wave represents the increase in atrial pressure that occurs while the atrium fills against a closed tricuspid valve. Finally, the "y" descent represents a drop in pressure as the ventricle relaxes, the tricuspid valve opens (because atrial pressure is higher than ventricular pressure) and blood passively enters the ventricle.

The central venous pressure waveform may be used in diagnosing pathophysiologic events affecting right heart function. For example, atrial fibrillation is characterized by absence of the normal "a" wave. Tricuspid regurge results in a giant "v" wave that replaces the normal "c, x and v" waves. The central venous pressure waveform can be also changed by other events as atrioventricular dissociation, tricuspid stenosis, pericardial effusion, pulmonary hypertension, increased ventricular afterload or right ventricular

ischaemia and failure. Any variation in cardiac rhythm that alters the normal relationship between the wave-form and the cardiac cycle will alter the wave-form morphology

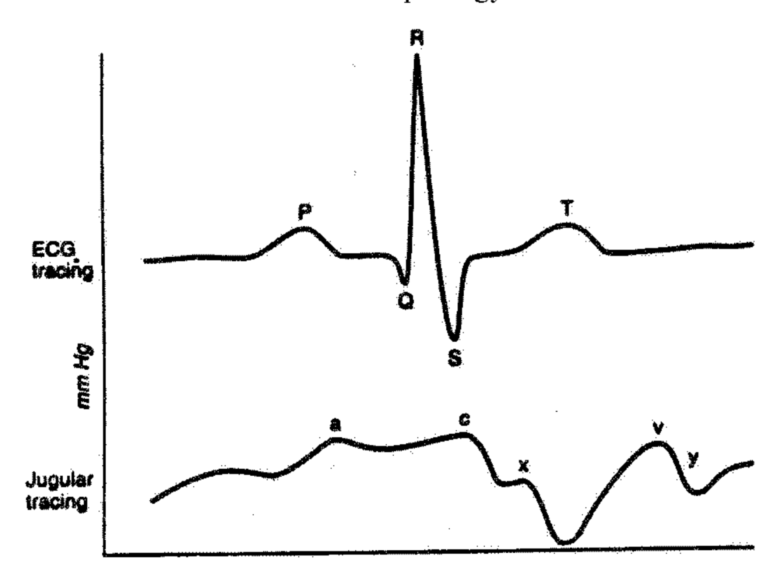


Figure 59: The upward waves (a, c, v) and the downward descents (x, y) of a central venous tracing in relation to the cardiac cycle.

4.12.2. The pulmonary artery catheter (PAC):

Since its introduction > 30 years ago, the PAC has become part of every day management in cardiology, anaesthesia and intensive care, but remains controversal [91]. The pulmonary artery floatation catheter is used to measure the pulmonary capillary wedge pressure (PCWP) for estimating left atrial pressures in patients with previous or existing right ventricular dysfunction. This is a measure of left ventricular end-diastolic pressure (LVEDP) as an indirect index for the left ventricular end-diastolic volume

(LVEDV) and myocardial fiber length. Measurement of PCWP is achieved through the Swan-Ganz catheter through a central vein (fig. 60). Once the catheter has been correctly placed into the pulmonary artery, and the balloon inflated, the catheter floats into a smaller pulmonary artery where the balloon wedges and the pressure in the distal circulatory bed falls to equilibrate with the left atrial pressure [92]. PCWP is measured via the distal lumen of the pulmonary circulatory bed. As with right atrial pressure measurements, correct zeroing and calibration are essential and measurements should be taken at end-expiration to avoid being influenced by the respiratory pressures.

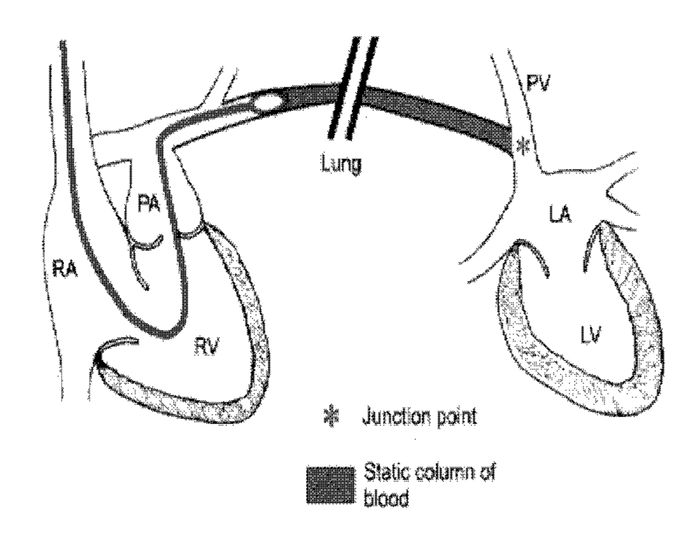


Figure 60 : Wedging of the pulmonary artery floatation catheter.

It is necessary to consider several factors when interpreting PCWP measurements. First, it is necessary to measure intravascular pressure, not airway pressure. Airway pressure will be measured if the catheter tip is in West zone I instead of West zone III of the lung which may be quite extensive in hypovolaemic patients or patients with acute respiratory distress syndrome (ARDS) ventilated with high inflation pressures [93]. Inspection of the pressure trace can reveal when airway pressure is being measured. This may need repositioning of the catheter so that its tip is below the left atrium. Second, there should be no interference with pulmonary venous drainage between the tip of the catheter and the left atrium as by pulmonary embolus. Third, there should be no significant gradient between the left atrium and the left ventricle as by mitral valve disease. Fourth, trends in individual patients, rather than absolute values, yield the most useful information, particularly in patients who already have significant circulatory or respiratory disease.

In patients with previously normal lungs, pulmonary congestion will be diagnosed if PCWP exceeds 18 mmHg, and frank pulmonary oedema if it exceeds 30 mmHg. However, patients with long-standing left ventricular failure or mitral stenosis may require pressures in excess of 30 mmHg for normal ventricular filling [94].

The pulmonary artery pressure trace should be continuously displayed and regularly inspected to ensure that the PAC does not creep and becomes wedged. (fig. 61) If the catheter wedges spontaneously or with balloon inflation volume of less than one ml of air, it should be slightly withdrawn. This reduces the chances of pulmonary arterial rupture with injudicious balloon inflation. It is

usually adequate to know whether pressures are normal, high or very high and to be able to observe trends with changes in management.

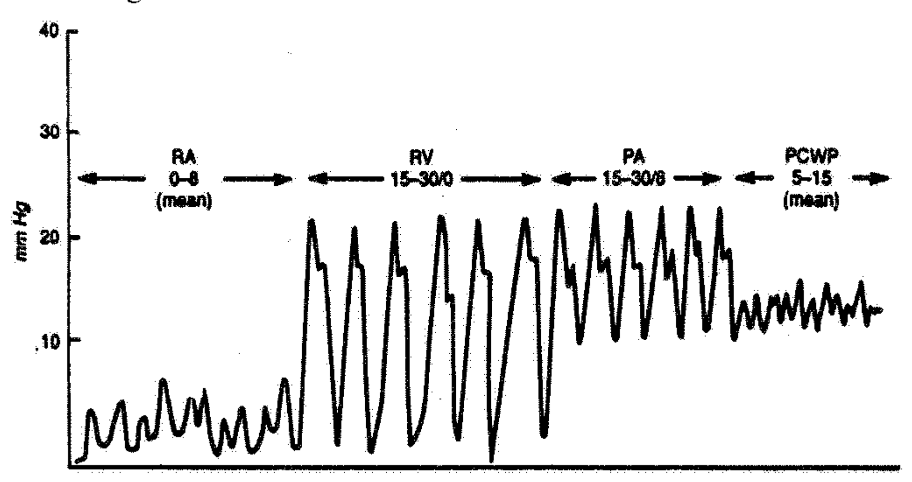


Figure 61 : Normal pressure values and waveforms as a pulmonary artery catheter is advanced from the right atrium to a wedged position in a pulmonary artery

Cardiac-output measurement achieved through thermodilution using a PAC and an appropriate output computer is both accurate and reproducible[95]. This needs PAC placement so that an undamped trace is obtained, with rapid injection of an accurate volume of 0°C injectate and taking the average of three measurements during the same portion of the respiratory cycle. Cardiac output measurements are warranted only in very ill patients, and their main use is in discriminating low and high cardiac output states, in observing trends and in obtaining cardiorespiratory derived variables.

The multipurpose pacing pulmonary artery catheter has been recently used. It includes three atrial and two ventricular electrodes for cardiac pacing (fig. 62)

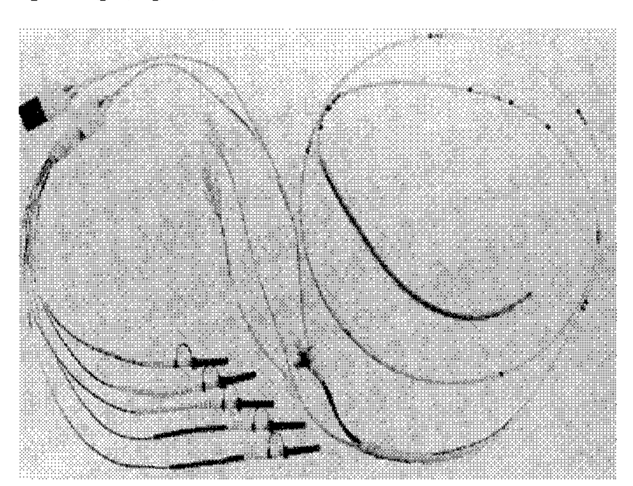


Figure 62 : The multipurpose pacing pulmonary artery catheter: three atrial and two ventricular electrodes

Truly mixed venous blood is obtained from the right ventricle or the pulmonary artery by the PAC, since superior or inferior vena cava blood is different in composition, and mixes during passage through the heart. Mixed venous oxygen saturation (SvO_2) is related to arterial oxygen content (CaO_2), oxygen consumption (VO_2) and cardiac output (CO). SvO_2 may be monitored continuously via a fiberoptic bundle on the PAC. It is an indicator of supply-demand relationship of oxygen (VO_2/DO_2) and is inversely proportional to the oxygen extraction ratio (O_2ER). It is an early indicator of impending haemodynamic failure and is a useful global oxygenation parameter especially in the presence of ventilation/perfusion (V/Q) mismatching or blood shunting (Qs/Qt).

Dual oximetry by SvO_2 and SpO_2 may be of important clinical value.

Monitoring hypovolaemia is an area in which CVP and PCWP measurements are involved. Over decades, hypovolaemia was assessed by using the Royal College of Surgeons scale [96]. Parameters included the amount of blood loss, the heart rate, the blood pressure, the pulse pressure, the respiratory rate, the urine output and the central nervous system condition. It included 4 severity classes. Losses of < 750 mls, 750-1500 mls, 1500-2000 mls and > 2000 mls of blood denote classes I, II, III and IV respectively. Escalating classes are accompanied by escalating changes of other clinical parameters. However, it is clear that patients may lose up to 1500 mls of blood with minimal clinical changes. Again, clinical changes may reflect patient anxiety or may be due to pharmacotherapy. It has been always shown that the addition of CVP and PCWP measurements and the TOE represents safe, reliable, rapid, cost-effective and better monitoring for assessing hypovolaemia.

A new modality for assessing volume status in patients who are being mechanically ventilated with positive pressure ventilation is that of pressure wave-form analysis. The arterial pressure wave-form – displayed through an arterial line – demonstrates a typical biphasic change with each mechanical breath. The initial response is an increase in the systolic BP, which is caused mainly by a squeezing effect of the inflated lungs on the pulmonary vasculature, leading to a transient increase in the LV preload. Such early inspiratory augmentation of LV stroke output can also result from

the after-load reducing the effect of increased intrathoracic pressure. The initial increase in the systolic BP is followed by a decrease, which is caused by a lower LV stroke output attributable to the reduction in venous return that is associated with the mechanical breath. The difference between the maximal and minimal values of the systolic BP during one mechanical breath is termed the systolic pressure variation. By using the systolic BP during a short (5s) apnea as a reference pressure, the systolic pressure variation can be divided into 'dUP' and a "dDOWN' components (fig. 63).

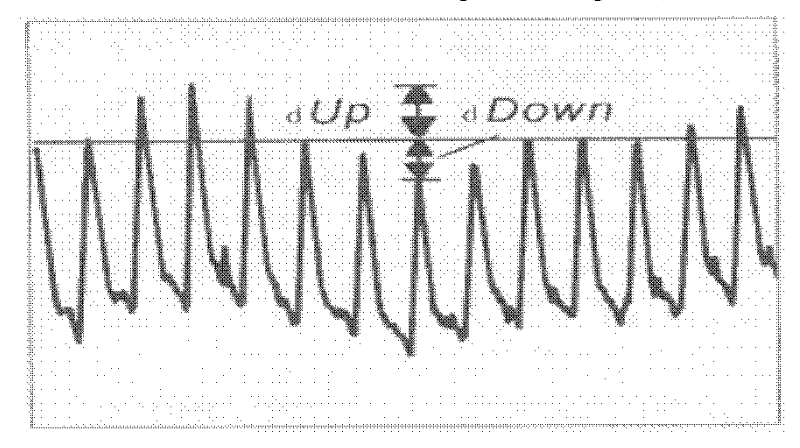


Figure 63: The systolic pressure variation is the difference between the maximal and minimal values of the systolic BP during one cycle of mechanical breath.

The dUP reflects the augmentation of the LV stroke output by the mechanical breath, whereas the dDOWN reflects the extent by which the reduction in venous return affects the LV stroke output. Patients with a reduced preload are more susceptible to the reduction in venous return with every breath, and therefore demonstrate a large dDOWN. Thus, the systolic pressure variation

is extremely helpful in differentiating hypovolaemia from heart failure as the cause of a low flow state. Low blood volume will be characterized by a large dDOWN, whereas poor myocardial function is typified by lack of a dDOWN and the possible appearance of a significant dUP. During hypervolaemia with or without left ventricular failure the dUP becomes the most prominent segment of the systolic pressure wave-form. In mechanically ventilated patients who do not have an arterial line, much of the same information can be obtained from observing the plethysmographic signal of the pulse oximeter (fig. 64). The wave-form of the oximeter responds to the cyclic changes in the intrathoracic pressure, and in hypovolaemia there is a large variability in the amplitude of the signal with every breath. [97]

So, in a critically-ill or injured patient, on mechanical ventilation, all that is needed to detect hypovolaemia is to closely monitor the arterial pressure wave-form, or the plethysmographic signal of the pulse oximeter, interpose a short apnea and observe the delta Down. A down in excess of 10% during apnea is highly suggestive of hypovolaemia. Fig (64) shows the respiratory-induced variation in the plethysmographic signal before and after the infusion of one liter crystalloid with the disappearance of delta Down variations following the infusion.

Intramucosal PH (Phi) monitoring by gastric tonometry, has been used to reveal early gut failure in different shock states including hypovolaemic shock [98]. Management of these cases through fluid therapy or pharmacotherapy or both aims to normalize Phi. Although gastric tonometry reveals regional VO_2/DO_2

relationship, monitoring of global VO_2/DO_2 reveals global relationship. Both relationships, representing both sides of the coin, can simultaneously monitor tissue perfusion and oxygenation, especially when trends of measurements are recorded, and both of them can guide therapy.

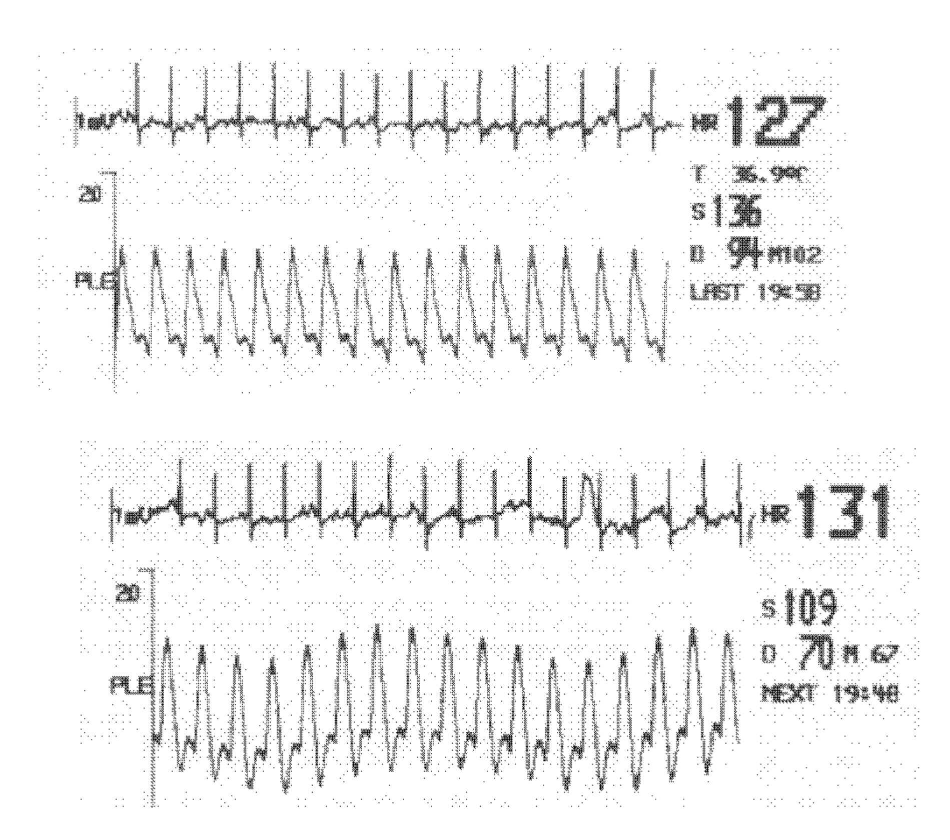


Figure 64: Variations in the plethysmographic signal before and after the infusion of one liter of crystalloid.

4.13. Derived cardiorespiratory variables:

Subjective information provided through medical history and physical examination seldom identifies actual abnormalities of cardiorespiratory function and are poor predictors of disease severity. The clinical picture is sometimes completed by monitoring abnormalities of gas exchange, pulmonary and chest wall ventilatory functions, and respiratory mechanics.

4.13.1. Monitoring gas exchange abnormalities:

Monitoring gas exchange abnormalities may be derived from primary variables and additional parameters as haemoglobin concentration and body surface area deduced from body weight and height. They include stroke volume (SV), stroke index (SI), cardiac output (CO), cardiac index (CI), stroke work (SW), stroke work index (SWI), systemic vascular resistance (SVR), pulmonary vascular resistance (PVR), systemic vascular resistance index (SVRI) and pulmonary vascular resistance index (PVRI).

Stroke Volume (SV): It is the volume of blood ejected by the ventricle per heart beat = $\frac{\text{cardiac output}}{\text{heart rate}}$. It also equals end-diastolic to-end-systolic volume difference, normally 70-80 ml per beat for a 70kg man at rest. It is affected by ventricular filling and preload, myocardial contractility and outflow resistance, and systemic vascular resistance.

Stroke Index (SI): It is the stroke volume divided by body surface area, thus accounting for the effect of body size, normally 30-50 ml/m^2.

Stroke Work (SW): It is the measurement of ventricular performance (usually the left ventricle), indicating the work done by the ventricle.

SW (g) = SV x (MAP-PCWP)x 0.0136, where:

0.0136 = correction factor for units, SW normally equals 60-80g.

Stroke Work Index (SWI): It is the stroke work divided by body surface area, normally 40-80 g/m^2.

SW and SWI are increased in hypertension and hypervolaemia and decreased in shock, cardiac failure and aortic stenosis.

Cardiac Output (CO): It is the volume of blood pumped by the heart per minute. It equals the SV x heart rate (beats/min), normally about 5L/min in a 70 kg man at rest. It may increase up to 30L/min with severe exercise.

Cardiac Index (CI): It is the cardiac output divided by body surface area. It equals 2.5-3.5 L/m^2 in a 70 kg man at rest.

CO and CI are of central importance in maintaining arterial BP (CO x SVR) and O_2 flux to tissues (O_2 delivery). They are affected by the metabolic rate, drugs and many other physiological and pathological processes which affect heart rate, preload, myocardial contractility and after-load. Approximate values for normal distribution of CO are : 5% for the heart, 14% for the brain, 20% for the muscles, 22% for the kidneys, 25% for the liver and 14% for the rest of the body.

Systemic Vascular Resistance (SVR): It is also known as the peripheral or total peripheral resistance. It is the resistance against

which the heart pumps. It is calculated using the principle of Ohm's law:

$$SVR = \frac{MAP - CVP\ (mmHg)}{CO\ (L/min)} \times 80\ (correction\ factor)$$

Normally 1000-1500 dyne/s/cm^{-5}.

Systemic Vascular Resistance Index (SVRI): It is the SVR divided by the body surface area to adjust for differences in body size between individuals. SVR increases progressively with age. Chronically increased SVR is the hallmark of essential hypertension. It is mainly determined by the diameter of the arterioles, small changes in their caliber producing large changes in resistance. Arteriolar caliber may be affected by intrinsic contractility of vascular smooth muscles representing myogenic autoregulation; locally-produced substances causing vasodilatation as CO_2, nitric oxide (NO) and adenosine; neural innervations through effect on adrenergic and dopaminergic receptors and circulating substances, as noradrenaline, adrenaline and vasopressin.

Pulmonary Vascular Resistance (PVR): It is calculated by using Ohm's law:

$$PVR = \frac{Mean\ PAP - LAP\ (mmHg)}{CO\ (L/min)} \times 80\ (correction\ factor)$$

Normally it is 90-120 dyne/s/cm^{-5}.

Pulmonary Vascular Resistance Index (PVRI): it is the PVR related to the body surface area.

PVR is distributed more evenly than in the systemic circulation, with approximately 50% in the capillaries and 20% in the veins. Pulmonary arteries are thin-walled, large in diameter and

easily distensible. The pulmonary circulation is more dependent on gravity, posture and the relationship between alveolar and intravascular pressures than on vascular muscle tone. It is affected by passive or active factors. Passive factors are cardiac output, intravascular pressures and lung expansion. Active factors are nervous control, hypoxia, drugs and hormones. Hypoxic pulmonary vasoconstriction (HPV) represents reflex vasoconstriction of pulmonary arterioles in response to low oxygen tension in the alveoli. It results from flow of blood away from lung areas with low oxygen content, helping to reduce V/Q mismatch. Hypoxaemia causes an increase in PVR with increased right ventricular work and increased right to left shunting, particularly if SVR is lowered. HPV is reduced by hypocapnia and vasodilators.

Other important cardio-respiratory gas exchange parameters include arterial oxygen content (CaO_2), mixed venous oxygen content (CvO_2), arterio-venous oxygen content difference ($Ca\text{-}vO_2$), oxygen delivery (DO_2), oxygen consumption (VO_2), oxygen extraction ratio (O_2ER), oxygenation index (OI), alveolar-arterial oxygen tension gradient, respiratory index, arterial/alveolar oxygen tension ratio, arterial-endtidal carbon dioxide tension gradient, ventilation/perfusion relationship (V/Q) and right to left shunt fraction (Qs/Qt).

Arterial oxygen content (CaO_2): It equals oxygen bound to haemoglobin and oxygen dissolved in plasma of arterial blood.

$CaO_2 = (Hb \times 1.34 \times SaO_2) + (PaO_2 \times 0.003)$, where :

Hb = haemoglobin concentration in g/dl, 1.34 = Hufners' constant, SaO_2 = arterial oxygen saturation of haemoglobin,

PaO_2=arterial oxygen tension of haemoglobin, 0.003 = oxygen in ml per mmHg dissolved in plasma. Normally, CaO_2 equals 20 volumes of oxygen percent of blood for a 70 kg adult man at rest. It is composed of 19.7 ml oxygen combined with haemoglobin and 0.3 ml dissolved in plasma.

Venous oxygen content (CvO_2): It equals oxygen bound to haemoglobin and oxygen dissolved in plasma of venous blood.

$CvO_2 = (Hb \times 1.34 \times SvO_2) + (PvO_2 \times 0.003)$, where:

SvO_2 = venous oxygen saturation of haemoglobin, PvO_2 = venous oxygen tension of haemoglobin. Normally, CvO_2 equals 15 volumes of oxygen percent for a 70 kg adult man at rest.

Arterio-venous oxygen content difference ($Ca\text{-}vO_2$): It equals the difference in oxygen content of arterial and venous blood = 20-15 = 5 volumes of oxygen percent of blood.

Oxygen delivery (DO_2): Calculated oxygen flux. It is the amount of oxygen delivered to the tissues per unit time. It denotes $DO_2 = CO \times CaO_2$. Normally 500-700 $ml/min/m^2$ if cardiac index is used.

Oxygen transport (TO_2) means the amount of oxygen transported to the tissues by the blood. It equals the amount of oxygen fluxed by the heart to the tissues. The actual amount of oxygen delivered to the tissues (DO_2) may be slightly less than the amount fluxed by the heart or transported by the blood. The difference is due to physiological or pathological arterio-venous shunting of the blood. To clarify this statement, imagine a postman carrying 100 letters to transport them to 100 individuals. This represents TO_2. If he delivered 98 letters only to 98 individuals, this

is DO_2. The missing 2 letters didn't reach 2 individuals because they were lost. This represents arterio-venous shunting without oxygenation.

Oxygen consumption (VO_2): It equals the amount of oxygen utilized by the tissues

VO_2 = [CO x C(a-v) O_2] = 240-270ml/min or 130-166 ml/min/m^2 if the cardiac index is used.

Oxygen extraction ratio (O_2ER): It is the relationship between VO_2 and DO_2 = 22-30%.

As DO_2 falls, a critical point is reached known as the critical point of oxygen delivery below which VO_2 falls. The first part of the graph represents supply independent VO_2 and the second part represents supply dependent VO_2 denoting anaerobic tissue respiration (fig. 65). Maintenance of supranormal values of 600 ml/min/m^2 for DO_2 and 170ml/min/m^2 for VO_2 have been suggested to increase survival in critically-ill patients. O_2ER is inversely proportional to SvO_2.

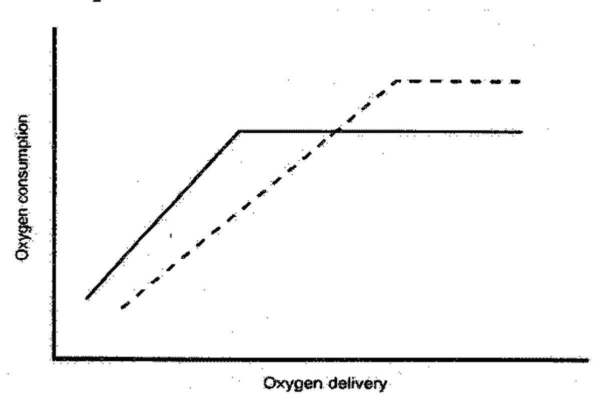


Figure 65: The oxygen consumption (VO_2) / oxygen delivery (DO_2) relationship. The inflection oint of each graph is the critical point of oxygen delivery

Oxygenation Index (OI): It equals the relation between arterial oxygen tension and the inspired oxygen fraction (FiO_2):

$$OI = \frac{PaO_2}{FiO_2}$$

In an adult with a healthy lung inspiring room air, OI equals 500. At a ratio of 300 it helps in diagnosing acute lung injury (ALI). Below 200 it helps in diagnosing acute respiratory distress syndrome (ARDS).

Alveolar-arterial oxygen tension gradient [P(A-a)O2]: It is deduced from the alveolar gas equation:

PAO_2= [(Pb-47) x (FiO_2] - $\frac{PaO_2}{RQ}$, where:

PAO_2 = alveolar oxygen tension, Pb= barometric pressure, 47 = water vapour pressure in the tracheobronchial tree in cmH_2O, R.Q = respiratory quotient representing the relation between CO_2 production and VO_2 due to the type of food consumed. The normal [P(A-a)O_2] in a healthy adult respiring room air equals 10 mmHg and can increase to 40 mmHg with age. It is a better parameter for gas exchange because it includes the barometric pressure and considers the $PaCO_2$.

The Respiratory Index (RI) [99,100]. It equals the [P(A-a)O_2] divided by the PaO2

$$RI = \frac{[P(A-a)O_2]}{PaO_2}$$

It ranges between 0.1 in a young adult and 0.5 in an aged person. It is a better oxygenation parameter.

The arterial/alveolar oxygen tension ratio [P(a/A)O_2][101]:

This ratio is a preferred oxygenation parameter to the $P(A-a)O_2$ because the ratio is not affected by changes in FiO_2 as the gradient. A ratio of 0.75 indicates hypoventilation, a ratio of 0.55 to less than 0.75 denotes V/Q mismatch while a ratio < 0.55 diagnoses shunting of blood[102].

The artertial-endtidal carbon dioxide tension gradient $[P(a-ET)CO_2]$:

It defines the diffusion status of the alveolar membrane. Normally it equals 3-5 mmHg. On this basis $PETCO_2$ can reflect $PaCO_2$. However, in pathological diffusion states, arterial blood gas (ABG) measurements become a must.

Ventilation/perfusion ratio (V/Q):

It represents the relation of alveolar ventilation to lung perfusion. In a normal healthy lung it equals 0.8 on FiO_2 0.21 of room air. When 100% oxygen is inhaled, a low SaO_2 increases confirming the diagnosis of V/Q mismatch.

The shunt equation (Qs/Qt):

It relates the shunt fraction of the blood to the total CO.

$$Qs/Qt = \frac{CcO2 - CaO2}{CcO2 - CvO2}$$ where,

CcO_2 = ideal end-capillary pulmonary arterial oxygen content

= ($Hb \times 1.34 \times SaO_2$) + ($PaO_2 \times 0.003$)

= ($Hb \times 1.34$) + ($PaO_2 \times 0.003$) as SaO_2 is a unity because blood is fully or 100% saturated.

Qs/Qt = can be also expressed as: $\frac{1 - SaO_2}{1 - SvO_2}$

When 100% oxygen is inhaled, a low SaO_2 does not show a parallel increase confirming the diagnosis of blood shunting.

Although absolute readings for cardiorespiratory variables are important for diagnosing gas-exchange abnormalities, trends of readings are of more diagnostic value. For example, sequential measurements of the shunt fraction may show changes with posture or total body consumption and are useful for optimising positive end-expiratory pressure (PEEP) or adjusting catecholamine dosage rates and observing changes in preload or afterload specially in patients with left ventricular dysfunction. Oxygenation Index trends can give valuable information about therapy and management of a critically-ill patient during the perioperative period.

The value of ABG analysis:

ABG analysis is indicated if the patient's symptoms, medical history, physical examination or laboratory data suggest significant abnormalities in cardio-respiratory or acid-base status. Repeated ABG analysis is helpful in evaluating the effects of treatment. Accurate interpretation of ABG measurements by a skilled physician requires knowledge of the full history and clinical picture. It is important to have preoperative control values and to know the inspired oxygen fraction (FiO_2). ABG components are important for monitoring different gas exchange variables as CaO_2 and DO_2, while mixed venous blood gas monitoring is important for CvO_2 and VO_2. ABG and mixed venous blood measurements can monitor the O_2ER. Other oxygenation parameters require data from one or the other or both through invasive techniques.

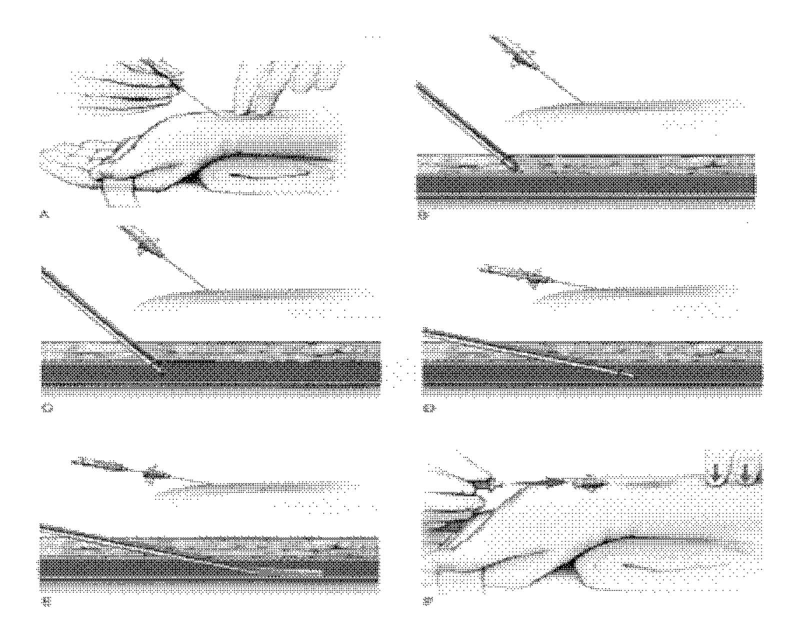


Figure 66 : Percutaneous radial artery cannulation.

Although several peripheral arteries can be used for cannulation (radial, brachial, femoral, dorsalis pedis, superficial temporal), the radial artery is the most commonly selected (fig. 66). Originally Allen's test was described for assessing arterial flow to the hand in thromboangitis oblitrans. Modified Allen's test is described for assessing ulnar artery flow before radial arterial cannulation. Both ulnar and radial arteries are compressed at the wrist, and the patient is asked to clench tightly and open the hand, causing blanching. Pressure over the ulnar artery is released; the colour of the palm takes less than 5-10 seconds to return to normal and over 15 seconds is considered abnormal. A similar manoeuvre may be performed with the radial artery before ulnar artery cannulation. Although widely performed, arterial cannulation is

sometimes complicated by ischaemic damage of the hand. An indwelling heparinized arterial cannula is useful for repeated ABG measurements and for direct BP monitoring as well.

The application of fiberoptics as sensors led to the devleopment of continuous intra-arterial blood gas monitoring. This has been recently introduced into the field of critical care offering reliability, ease of use and the ability of the critical care practitioner to obtain accurate ABG analysis at bed-side. This type of monitoring is a real-time method for concomitantly assessing oxygenation, ventilation and acid-base status to provide diagnosis and to guide therapy in critically-ill patients.

4.13.2. Monitoring pulmonary and chest wall ventilatory functions:

Sufficient information regarding pulmonary ventilatory functions can be achieved by using the famous pulmonary function tests together with monitoring respiratory mechanics.

Pulmonary function tests:

Abnormalities of ventilatory functions of the lungs and chest wall can be monitored by pulmonary function tests. These tests have assumed an increasing role in preoperative evaluation of many surgical patients, aiming to identify those with abnormal gas exchange to improve their outcome by reducing postoperative complications.

The cornerstone of pulmonary function testing is clinical spirometry. Before defining each part of the spirogram, it is

important to note that volumes are single compartments in the lung. Adding two or more volumes together results in what is called a capacity. Volumes and capacities are expressed as percentage of normal. Plus or minus 20% of the predicted value is the normal range of different volumes and capacities. Routinely identified volumes and capacities (fig. 67) include: tidal volume (V_T), inspiratory reserve volume (IRV), inspiratory capacity (IC), residual volume (RV), expiratory reserve volume (ERV), functional residual capacity (FRC), closing capacity (CC), vital capacity (VC) and total lung capacity (TLC).

As the lungs become reduced in volume during expiration, there comes a point at which some small airways begin to close (closing volume: CV) and therefore prevent any further expulsion of gas from related alveoli, so that air trapping occurs. The lung volume at which this phenomenon is detected is the closing capacity (CC) which equals closing volume and residual volume (RV).

The commonest measurement of lung function is the vital capacity (VC). This is the largest volume monitored after an individual inspires deeply and maximally to total lung capacity (TLC) and then exhales completely to residual volume (RV) into a spirometer. A given VC is generally considered abnormal if it falls below 80% of the predicted value. Patients with abnormally low VC often have restrictive lung disease as pneumonia, atelectasis or lung fibrosis. This may also occur in obese patients with healthy lungs and in those with muscle weakness.

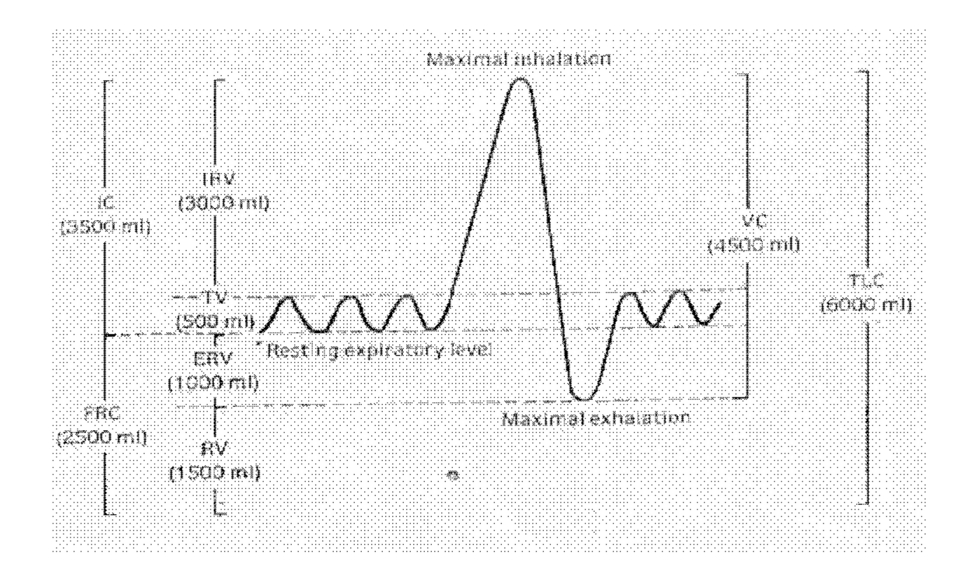


Figure 67: Lung volumes and capacities from a normal spirogram

If after a maximal inspiratory effort a subject exhales as forcefully and rapidly as possible, the exhaled volume is monitored with respect to time and is termed the forced vital capacity (FVC). The rate of flow during this rapid forceful exhalation indirectly reflects flow resistance properties of the airways. In the presence of airway obstruction, FVC tends to be less than the standard VC due to air-trapping. The FVC is reduced by the same conditions which reduce the VC.

In order to identify airway obstruction, flow rates are determined by calculating the exhaled volumes during certain time intervals. Most commonly measured by spirometry is the volume exhaled in the first second (FEV_1). FEV_1, is expressed as absolute

volume in liters or as a percentage of the FVC (FEV_1/FVC). Normal healthy subjects can exhale 75-80% of their FVC in the first second, the remaining volumes are exhaled in additional 2 or 3 seconds. Obstructive airway disease as bronchial asthma reduces expiratory flow rate, and thus reduces FEV_1 and FEV_1/FVC. Restrictive lung disease is not usually associated with airway obstruction and may cause decreases in FVC, with usually normal FEV_1/FVC.

The peak expiratory flow rate (PEFR) is obtained from the FVC spirogram or from PEFR gauges (fig. 68). Normal values in healthy males under 40 years of age are typically 500L/min or more. Values less than 200L/min in the surgical patients suggest impaired cough efficiency and strong likelihood of postoperative complications. Again, PEFR measurements can be utilized to monitor therapeutic responses in acute asthma.

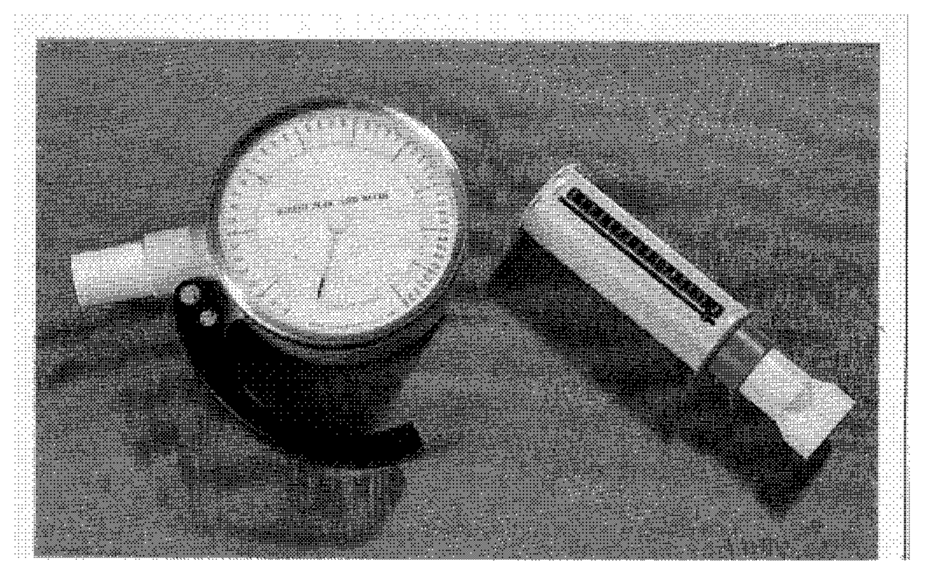


Figure 68: Types of peak expiratory flow-rate gauges

To identify airway obstruction, flow is measured from flow volume loop over the middle half of the FVC (FEF $_{25\text{-}75}$), known as the "effort independent flow", and equals 4.5-5.0L/sec in healthy young males (fig. 69). These values are usually normal when FEV_1/FVC is 75% or greater. Thus, the FEF $_{25\text{-}75}$ parameter is sensitive because the first 25% of the exhaled curve is disregarded due to the lung's initial interia, and the last 25% is disregarded due to effort dependency.

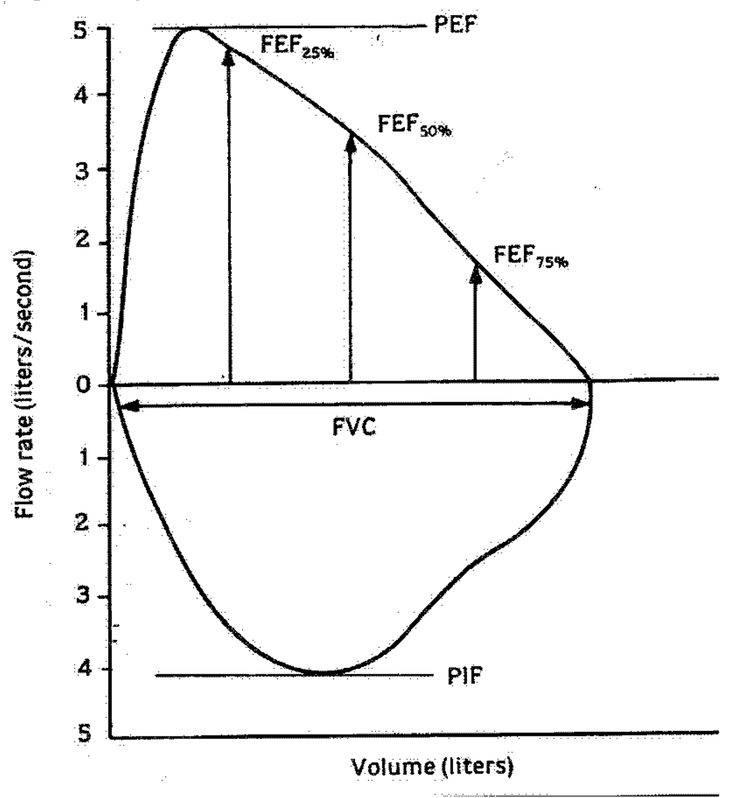


Figure 69 : Flow volume loop: peak expiratory flow (PEF); peak inspiratory flow (PIF); forced expiratory flow at X% of FVC (FEF%); forced vital capacity (FVC)

Dynamic lung function is also routinely evaluated by measuring the maximum breathing capacity (MBC) known as the maximal voluntary ventilation (MVV). This is the largest volume that can be breathed by voluntary effort per minute. The patient is instructed to breath as hard and as fast as possible for 12 seconds and the volume is extrapolated to one minute and expressed as L/min. MVV is usually reduced in patients with obstructive airway disease and correlates well with FEV_1. In healthy male adults, MVV averages 150-170 L/min. Values less than 80% indicate gross impairment in respiratory function.

Pulmonary function tests are used to identify and evaluate obstructive and restrictive respiratory disorders. Obstructive defects cause reductions in the measurements of flow, including FEV_1/FVC, FEF_{25-75} and PEFR. The VC is normal in mild obstructive disease but decreases as the obstruction becomes more severe. FRC and TLC are initially normal, to be mildly increased with acute airway obstruction but increase significantly with chronic defects, such as emphysema. Measurement of dynamic lung function by MVV shows a reduction in severe obstructive disease.

Restrictive lung disorders are identified by a reduction in VC, RV, FRC and TLC while measurements of flow may be normal or mildly reduced. The FEV_1/FVC is normal in pure restrictive disorders.

4.13.3. Monitoring respiratory mechanics:

Monitoring respiratory mechanics gives reliable information about the patient condition and his response to therapy. Measurements of compliance, airway resistance, work of breathing

and other parameters are important variables for assessment of respiratory mechanics.

4.13.3.1. Compliance:

Compliance is defined as volume change per unit pressure change. Thus, it is a measure of distensability of the lung and chest wall. The total pulmonary compliance is the product of the collapsing forces of the lung and the expansive forces of the thorax. It is expressed by the following equation:

$1/C_T = 1/C_L + 1/C_{TH}$, where:

C_T = total system compliance = 100ml/cmH_2O

C_L=lung compliance = 200ml/cmH_2O

C_{TH} = thoracic compliance = 200ml/cmH_2O

The total system compliance is more frequently used because of its ease of measurement. It requires measurements of volume and pressure at the proximal airway. This recoil pressure can be made either at the point of peak inspiratory pressure (PIP) or at end-inspiration after an inflation pause or hold, known as plateau pressure (Pplat) as shown in figure (70).

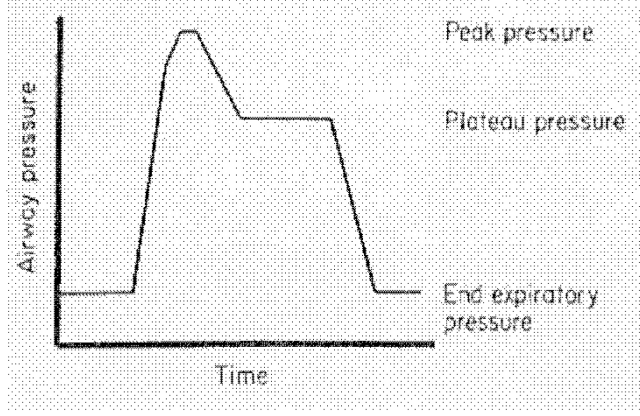


Figure 70 : Typical airway pressure trace

Compliance is divided into two components; static denoting alveolar stretchability (all opposing forces of the lung and chest wall) and dynamic denoting airway resistance (elastic properties of the lung only).

Static compliance (50-100 ml/cmH_2O) is measured by using the inspiratory pause method and the plateau pressure. This single tidal breath method using the static compliance technique is the most common method used during mechanical ventilation (fig.71)[103]. It is carried out by either manual occlusion of the expiratory limb or adjustment of the ventilator to cause an inflation pause to determine end-inspiratory or plateau pressure, while V_T is measured by a spirometer. The inflation hold should be 1-2 seconds long, to ensure that intrapulmonary airway pressure is at equilibrium throughout.

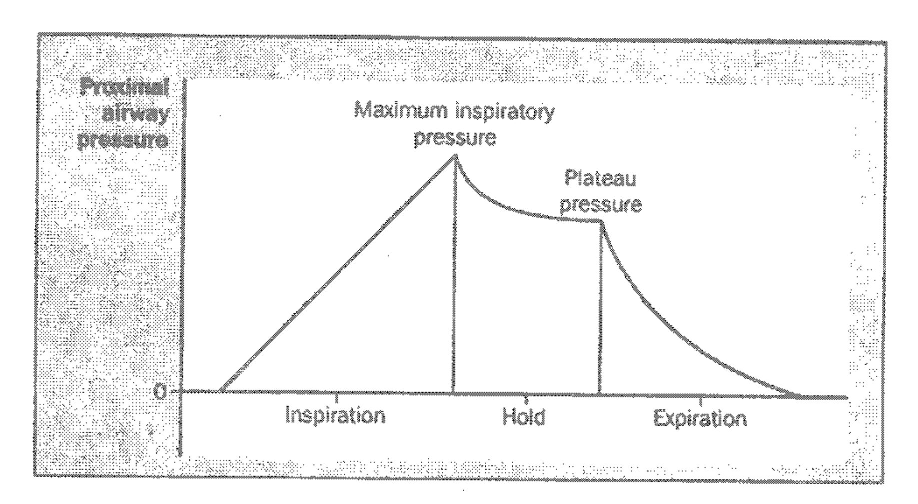


Figure 71: The single breath technique: starting from zero-end-expiratory pressure, an end-inspiratory hold is performed to determine static or plateau pressure (Pplat)

The multiple pressure-volume method has been developed as an extension of the single tidal breath method. It entails the measurement of V_T, PIP, P_{plat} and PEEP at different levels of V_T or PEEP. The results are then plotted graphically for analysis (fig. 72)[104].

Dynamic compliance (100-200 ml/cmH_{20}) is measured by using PIP at end-inspiration. Dynamic compliance reflects both the compliance and airway resistance properties of the lungs and thorax because of the use of the PIP, which makes it a mixed and complex signal that can be more difficult to interpret when used alone.

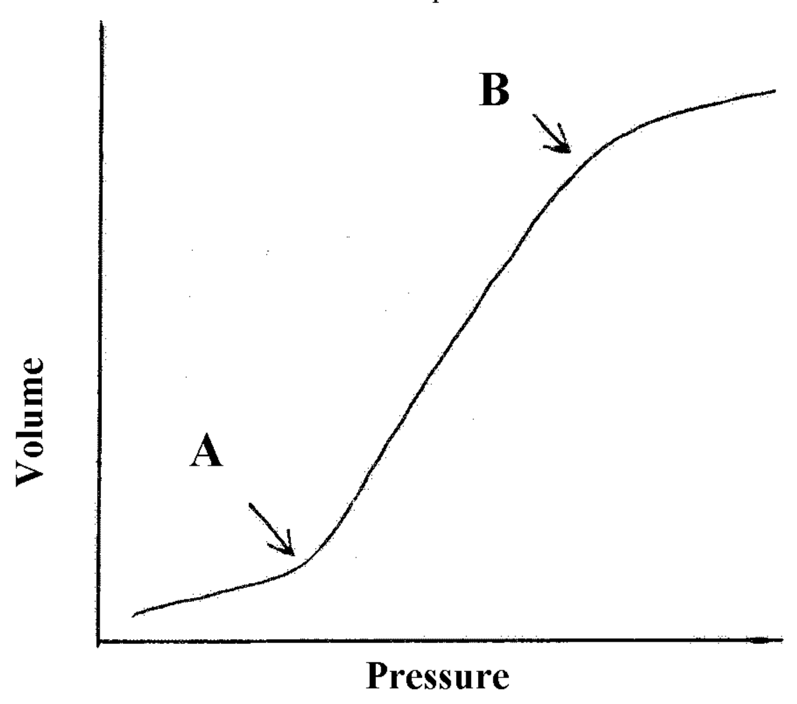


Figure 72 : The multiple breath technique to construct the compliance-volume curve

Computerized systems for continuous monitoring of the dynamic and static compliance have been developed for adults and paediatrics and proved useful for management of ventilatory support[105].

Determining trends of compliance can indicate acute changes as main-stem bronchial intubation, pulmonary barotrauma, oedema, atelectasis, bronchospasm or retension of secretions with decreases in both static and dynamic components. Factors that mainly affect airway resistance as bronchospasm and secretions cause more significant decline in dynamic compliance because of its sensitivity to changes in airway resistance.

It is known that 10-15 ml/kg is an accepted volume limited breath during mechanical ventilation for an adult with normal body weight. However, patients with acute respiratory distress syndrome or who are hypovolaemic may show an adverse response to such a volume. In this condition, the pressure-volume or compliance-volume curve can evaluate the proper volume. [106, 107]

Transpulmonary pressure represents the difference between alveolar and intrapleural presure. The former is measured at the mouth during periods of no gas flow, e.g. with the lungs held partially inflated and a few seconds allowed for stabilization, or using a shutter at the mouth to interrupt flow momentarily. Intrapleural pressure is measured using a balloon positioned in the lower third of the oesophagus. The resulting pressure-volume curve is approximately linear at normal tidal volumes (fig. 73). Different curves are measured during lung inflation and deflation (hysteresis); this is thought to represent the effects of surface tension.

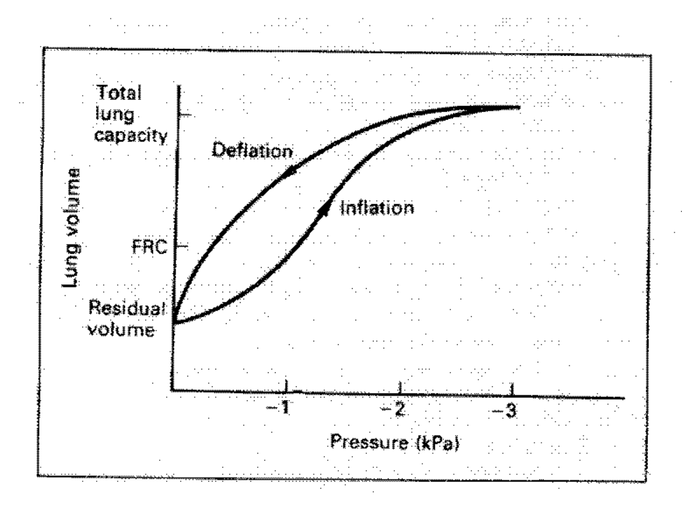


Figure 73: The pressure – volume curve of the lung

Compliance-volume curves may be established from the multiple breath technique (fig. 72). The previously mentioned multiple breath technique is used to plot the relationship between the pressure applied to the patients' lungs and the volumes that result. This actually plots a compliance-volume curve. Both the static and dynamic compliance increase as recruitable areas of atelectatic lung open, the so-called lower inflection point at A. Then the compliance increases significantly with increasing V_T till a point where compliance begins to decline denoting overdistension or over-inflation of individual lung units, the so-called upper inflection point at B. Lung damage may be produced or increased when patients' lungs are ventilated at volumes both below the lower inflection point and above the upper inflection point. Thus, the new ventilation strategy seeks to carry out tidal ventilation between points A and B on the curve. This means that a certain minimum

PEEP level is required, but that V_T must be kept small so that end-inspiratory plateau pressure (Pplat) does not exceed that at the upper inflection point. Some authorities recommend determining the lower and upper inflection points for each ventilated patient through constructing the compliance-volume curve. Ventilation usually stays between points A and B using PEEP of 8-15 cmH_2O and V_T of 5-8 ml/kg. In addition, because an alveolar distending pressure of 30-35 cmH_2O is the injury threshold, efforts should be made to keep Pplat below this level, for proper oxygenation without hazards of barotrauma, volutrauma or negative haemodynamic sequences.

Effective compliance:

As has been pointed out by Marini [108], the measurement of compliance in patients passively ventilated requires total PEEP (auto PEEP plus applied PEEP) and ventilator tubing compliance to be considered when effective static compliance is determined.

$$C_{static} = \frac{(VT) - (P_{plat} - PEEP_{tot})(\text{Compressible volume factor})}{P_{plat} - PEEP_{tot}}$$

Where, P_{plat} is the plateau pressure, $PEEP_{tot}$ is the total PEEP, and the compressible volume factor is the volume compressed in the ventilator circuit/cmH_2O. At present, some ventilators consider compressible volume, others consider auto-PEEP, but none considers all the preceding variables. As a result, the accuracy of any compliance measurement, regardless of ventilator, must be questioned.

4.13.3.2. Resistance:

During ventilatory support, the total resistance to gas flow is due to resistances of the pulmonary system, the endotracheal tube,

the breathing circuit and the performance of the gas delivery system. Expiratory airway resistance results from friction in the patient airway, ETT and expiratory limb of the circuit of the ventilator during expiration only. The generated resistance will differ during inspiratory and expiratory phases of ventilation as it differs during spontaneous or controlled ventilation.

Normally, airway resistance (Raw) is greater during expiration than during inspiration and increases with any disease process that causes narrowing of the airway as inflammation, oedema or bronchoconstriction. Raw increases during general anaesthesia due to reduction of FRC, bronchospasm and resistances in the artificial airway and the breathing system.

Normal Raw in an adult is 0.5-3.0 $cmH_2O/L/s$ at a flow rate of 0.5L/s. It is reported as a percentage of normal and a report of 100% ± 20% is considered normal. For proper patient management, it is useful to document how abnormal the Raw is.

Intrinsic Raw is determined by the pressure drop from the airway inlet to the alveoli during a measured flow rate by using the equation [109]:

Raw = $\frac{(Paw - Palv)}{V}$, where:

Raw = airway resistance ($cmH_2O/L/s$),

Paw=proximal airway pressure (cmH_2O),

Palv= alveolar pressure (cmH_2O) and

V = flow rate (L/s).

Bone [110] has described an airway occlusive method at end-inspiration during mechanical ventilation to calculate the inspiratory

effective Raw of the total respiratory system, using the following equation:

Reaw = $\frac{(PIP - Pplat)}{V}$, where:

Reaw = effective airway resistance of the total system (cmH_2O), PIP = peak inspiratory pressure (cmH_2O), Pplat = plateau or hold pressure (cmH_2O) and V=end-inspiratory flow during constant flow inflation (L/s).

When the flow is suddenly occluded at end-inspiration, the pressure at the airway suddenly drops from a peak value (PIP) to the static elastic recoil pressure (Pplat) throughout the system, which is the alveolar pressure (Palv). The difference between PIP and Pplat is a function of the total resistance from the proximal end of the artificial airway to the alveoli and the gas flow rate (fig. 70). The measurement of the Reaw is a simple extension of the static effective compliance measurement. It requires the additional information of end-inspiratory flow just before airway occlusion. The set inspiratory flow of the ventilator can be used as an estimate of flow if it is a constant flow from a calibrated high-pressure drive system. The patient must be relaxed with no inspiratory effort. The breath-to-breath stability of PIP and Pplat are indicators that the patient is not making inspiratory effort. The added resistance of the artificial airway should be included to eliminate its effect on the total Raw. The following equation determines the added resistance by various sizes of endotracheal tubes at different air flow rates [111] :

$P_r = {}_aV^b$, where

Pr = artificial airway resistance pressure ($cmH_2O/L/s$), V= gas flow, a=gas flow resistance constant at a flow of 0.1L/s and b=constant for index of shape.

Measurement of the Raw has been useful as a means of monitoring the effectiveness of bronchodilator therapy. COPD patients who are mechanically ventilated can show drops in PIP, Pplat and PEEPi (intrinsic PEEP) after delivery of aeorsolized bronchodilator to improve pulmonary function.

PEEPi (auto PEEP or occult PEEP) is due to dynamic hyperinflation of the lung in COPD patients. It is a positive intrathoracic pressure at the end of expiration denoting air-trapping. It may be encountered because of the use of improper respiratory settings during mechanical ventilation, including the use of large V_T, short expiration time, low peak inspiratory flow added to expiratory airway obstruction. It can lead to barotrauma or impaired cardiorespiratory functions specially in the hypovolaemic patient. Increased work of breathing (WOB) and hypoxaemia may lead to respiratory failure in the spontaneously breathing patient. To understand the pathogenesis of PEEPi, remember that most Raw resides in the large and medium-sized bronchi and that severe damage to the small airways may occur before a measurable increase in resistance. At low lung volumes, the radial traction produced by lung parenchyma surrounding the airways holding them open, is reduced. Thus, the airway caliber is reduced and the resistance is increased. During forced expiration, some airways may close causing air-trapping. It can be estimated either by using increments of PEEP and observing the airway pressure or the

clinical response of the patient to the addition of PEEP. It can be measured by the expiratory hold technique or the oesophageal pressure as an estimate of intraplural pressure (Ppl). Management needs a smaller V_T, a longer expiration time and an imposed small extrinsic PEEP with a value less by 2 cmH_2O than the measured value.

4.13.3.3. Work of breathing:

The work of breathing (WOB) denotes the muscular force needed to overcome the elastic properties of the lungs, thorax and abdomen to move a volume of air in and out of the lungs (fig. 74). In other words, the WOB has been described as the work necessary to overcome the "afterload" imposed on the respiratory system [112]. This work is performed by the respiratory muscles during spontaneous respiration, by the ventilator during controlled ventilation, or by both during partial ventilatory support. It can be assessed by simple observation and clinical examination of the patient or by measuring the mechanical work needed by the patient to breath.

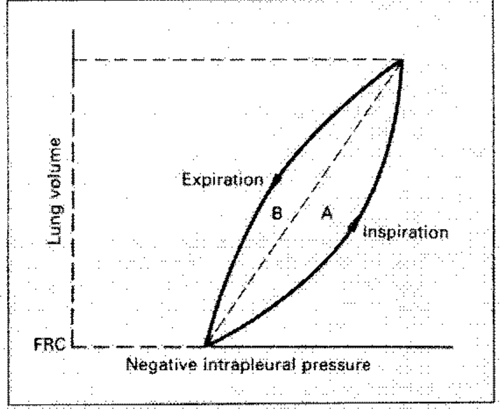


Figure 74: Intrapleural pressure against lung volume during breathing

Endurance is the ability of a muscle to sustain effort and is determined by the balance between supply and demand of muscular energy. Hypoxaemia, anaemia and ischaemia are especially important to correct because working muscles require an adequate flow of well-oxygenated blood for optimal performance.

By simple observation, it is easy to see the patient with increased WOB moving his or her chest and abdominal wall, using accessory respiratory muscles and breathing loudly in an abnormal way. By physical examination the respiratory rate exceeds 30/min in an adult and 60/min in an infant. V_T exceeds 7 ml/kg in an adult and is less than 3 ml /kg in an infant. The patient usually shows signs of an obstructive or restrictive lung disease using his or her accessory muscles to be able to breath; in a rapid and shallow manner. The patient may sit up to breath with the chest partially supported by resting on the elbows while pursing the lips. Pardee et al [113] indicated six parameters needed for mechanical ventilation of a patient with increased WOB:

- Pulse rate < 70 or > 120/min.
- Respiration rate > 30 breath/min.
- Palpable scalene muscles during inspiration.
- Palpable abdominal muscles during expiration.
- Irregular respiratory rhythm with apneic periods.
- Inability to respond to commands or coma.

The absence of these parameters denoted 90% chance of favourable outcome. The presence of one or two of these parameters points to >50% need for ventilatory support. The presence of three

or more parameters indicates the need for mechanical ventilation with the probability of death.

In the simplest form, work is performed when an applied force moves its point of application a given distance. This is described by the equation:

Work = Force (kg) x Distance (m)

When applied to the respiratory system, work is performed when a pressure (force divided by area) changes the volume of the system (distance times area). This is described by the equation:

WOB (J/L) = Pressure (Kg/m^2) x Volume (m^3)

The principal physiological components of the WOB are the elastic (work performed by the lung and chest wall when a change in volume occurs) and flow-resistive (work performed to overcome airway, tissue and viscous resistance to gas flow). In critically-ill patients, an additional component exists: the imposed work of breathing (WOBi) due to partial ventilatory support. The patient has to breathe through the ETT or tracheostomy tube, the breathing circuit and the ventilator.

During quiet breathing, the WOB is performed completely by the inspiratory muscles. Expiration is usually passive. Energy is still required for expiration. During inspiration, work performed by the inspiratory muscles is spent overcoming the forces opposing inspiration and, in addition, some work is stored as potential energy in the chest by distension of elastic elements. It is this potential energy that is used to overcome the flow-resistive work of expiration, with the remainder dissipated as heat. Active expiration can exist in COPD, asthma and during exercise.

Measurement of mechanical WOB:

The total WOB is estimated more commonly and accurately by measurement of pressure over-time. Measurement of oesophageal pressure is typically used as an estimate of intrapleural pressure (P_{pl}). Simultaneous measurement of airway pressure (P_{aw}) allows estimation of transpulmonary pressure ($P_{pl} - P_{aw}$). The pressure being integrated defines the aspect of work being measured; P_{aw} includes work done by the lungs, chest wall and inspiratory apparatus; transpulmonary pressure equals work done by the lungs alone, and transthoracic pressure ($P_{ATM} - P_{PL}$) is the work performed by the chest wall.

In 1958, Campbell published a method of measurement of the mechanical WOB in a spontaneously breathing subject [114]. This classic description forms the basis for most assessments of the mechanical WOB. Campbell constructed two pressure-volume diagrams during quiet inspiration (fig. 75) and expiration (fig. 76). Then a combined diagram was constructed to describe the total metabolic cost of the WOB in joules (fig. 77). In Campbell diagram, the area AIBCA describes the total metabolic cost.

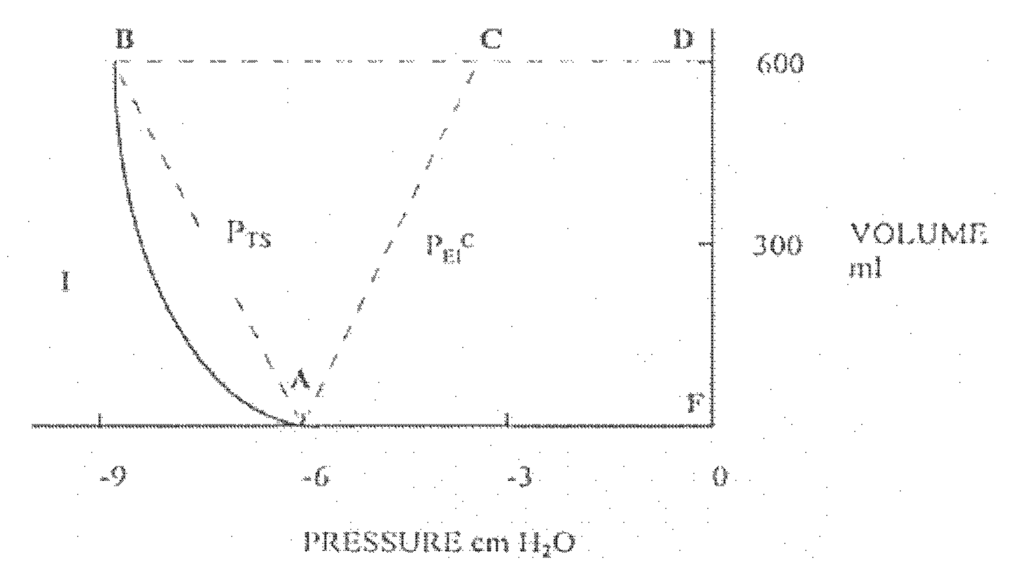


Figure 75: The pressure-volume diagram during quiet inspiration. The area AIBA represents the flow resistive work of inspiration. The area ABCA represents the elastic work performed by the respiratory muscles.

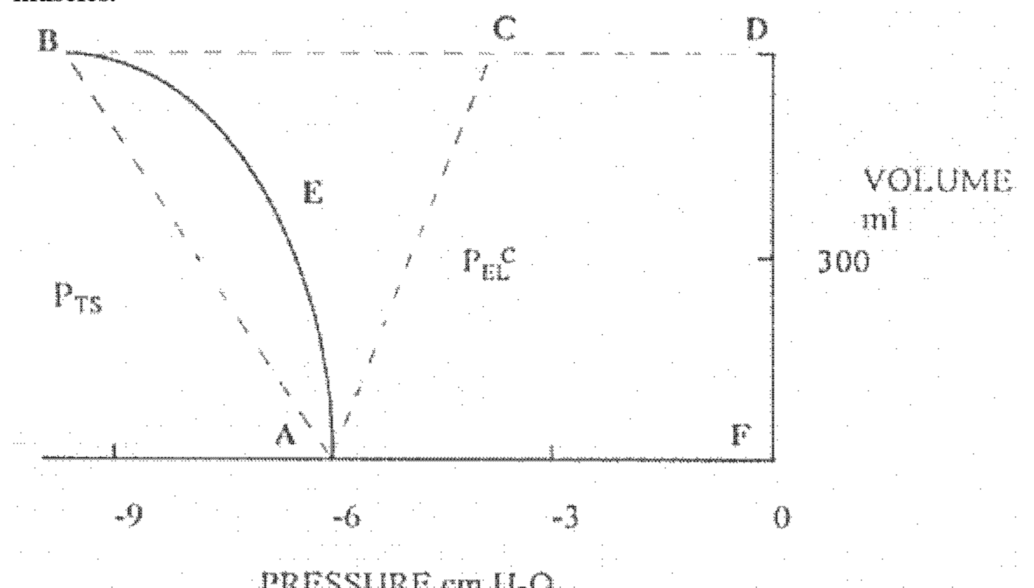


Figure 76: The pressure-volume diagram during quiet expiration. The area ABEA represents the flow resistive work of expiration.

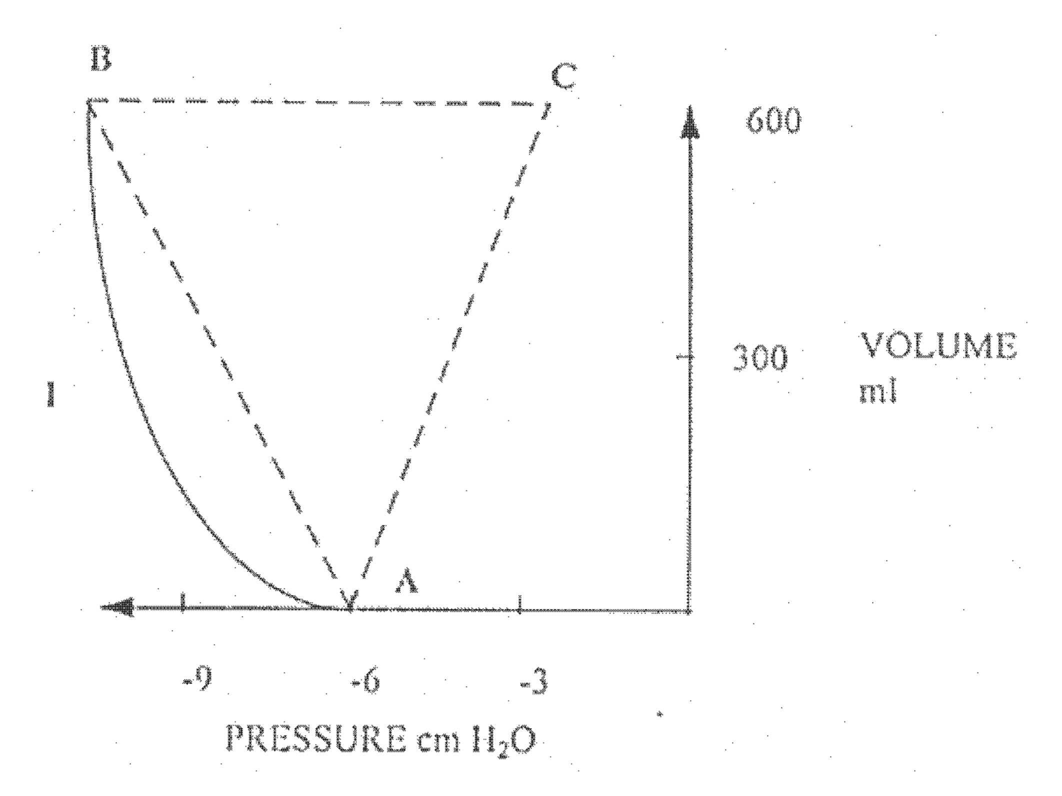


Figure 77: The Campbell diagram combining the pressure-volume diagrams during quiet inspiration and expiration. The total metabolic cost of breathing is represented by the area AIBA.

The Campbell diagram allows the calculation of mechanical work and metabolic cost of breathing performed during either spontaneous breathing or partial ventilatory support. WOBi may occur with all modes of partial ventilatory assistance, all ventilators, all circuits, and in all patients. In the spontaneously ventilating patients, WOBi is measured by integration of a pressure-volume loop[115]. Integration of pressure change measured at the tracheal end of the ETT calculates the WOBi of the entire system. Integration of pressure change at the Y-piece of the breathing circuit allows

calculation of the imposed work of the ventilator. Imposed work can be represented by a modified Campbell diagram (fig. 78). The area AICDA represents the physiological work of breathing. The area ABCDA represents the total work which equals the sum of the physiological and imposed components.

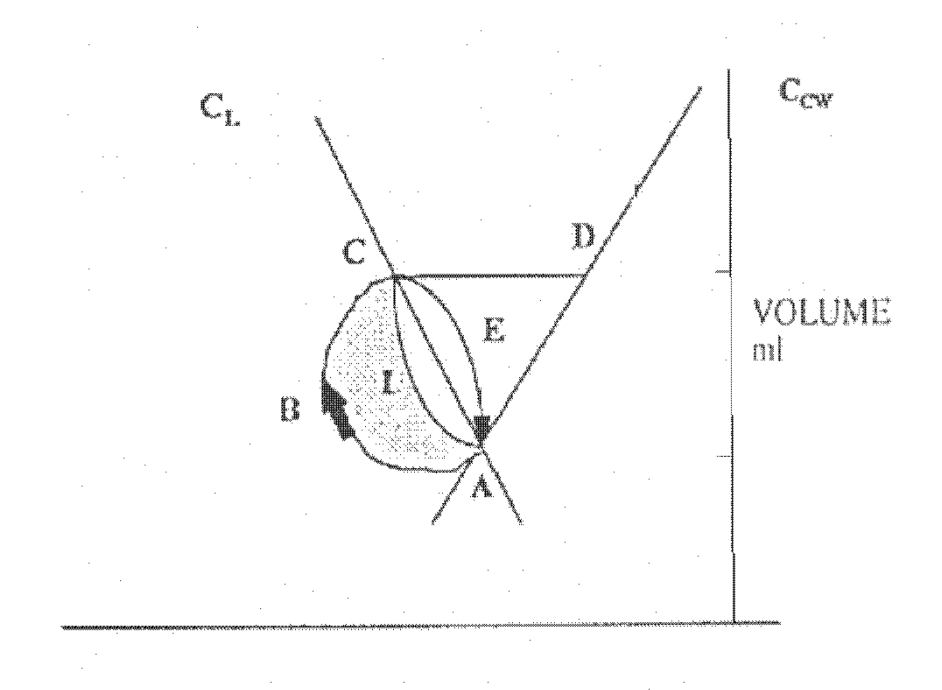


Figure 78: Modified Campbell diagram depicting the imposed flow-resistive work of breathing (shaded area). The area AICDA represents the physiological work of breathing. The area ABCDA represents the total work which equals the sum of the physiological and imposed components.

In a paralysed mechanically ventilated patient, the total WOB can be measured by calculating the area enclosed within an airway pressure –volume loop (fig. 79) or adopting the integral of pressure volume loop or flow: [116]

W_T = fPaw x Vdt, where:

W_T = total work of breathing (Kg/m), Paw = proximal airway pressure (cmH_2O) and Vdt = flow per unit time or volume (L).

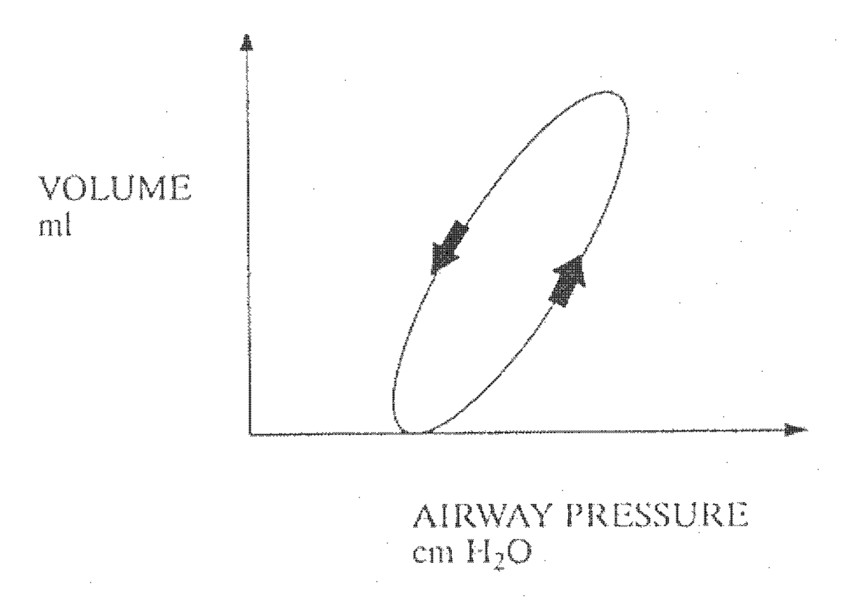


Figure 79 :Airway pressure-volume loop in an anaesthetized, paralysed patient. The enclosed area is the total mechanical work performed.

Marini et al [117] developed a simple bedside method for estimating the total inspiratory mechanical work during passive positive pressure ventilation using the equation:

$$Wi = \frac{[PIP - Pplat / 2)xVT]}{100}, \text{ where:}$$

Wi = inspiratory work per breath (kg/m), PIP= peak inspiratory pressure (cmH_2O), Pplat = plateau pressure (CmH_2O) and V_T = tidal volume (L). With the patient not making any inspiratory effort, the amount of inspiratory work per minute is calculated by multiplying Wi by the ventilator rate.

The normal values for the total inspiratory mechanical WOB during normal ventilation are 0.5-1.0 and 0.2-0.3 kg/m/min for the adult and newborn respectively. Ventilatory support is indicated if the WOB exceeds 1.7 and 0.8kg/m/min for the adult and newborn respectively. [118]

During the management of a ventilated patient with increased WOB, it should be remembered that the size of the endotracheal tube, the type of the gas delivery system and the exhalation valve in the ventilatory system may add substantial work to both inspiration and expiration. Such a work load should be reduced to minimum during ventilation and management of the disease process to avoid ventilator-dependent patient outcome.

Recently, computerized pulmonary monitors are designed to allow easy determination of WOB at the bedside and are commercially available for every day clinical use [119]. They contain software that provides automated measurements of ventilation, pulmonary mechanics, WOB and respiratory drive. An oesophageal balloon measures intra-oesophageal pressure and a pneumotachograph positioned between the Y-piece and the patient measures flow and airway pressure. Chest wall compliance is measured with the patient relaxed and the value is stored. Two WOB values are displayed: the patient WOB (WOBp) derived from

a Campbell diagram and the ventilator WOB (WOBv). The aim of ventilatory support is to titrate and to balance between both components of WOB to a non-fatiguing patient overload. It should be noticed that pressures measured in the ventilatory circuit are reflective, but not equivalent to pressures measured in the lung or the pleural space. During CPAP (spontaneous respiration) pressures measured internal to the ventilator on either the inspiratory or expiratory side under-estimate the pressure change occurring at the airway.

4.13.3.4. Other respiratory mechanics:

1. Respiratory drive:

It measures the neural drive to stimulate the force of diaphragmatic contraction. It is defined as oesophageal pressure changes during the first 100 seconds in cmH_2O. Normal values: 2-4cmH_2O. Higher values increase energy expenditure and lower values indicate blunted respiratory drive. Weaning from mechanical ventilation is possible at $<6cmH_2O$.

2. Respiratory time fraction (Ti/Ttot):

It indicates endurance as the ratio of inspiratory time to the total time of the respiratory cycle. Normal values: 0.3-0.4 and a marked decrease indicates impending respiratory failure. Increase of >0.1 from pre-weaning value correlates with unsuccessful weaning.

3. Pressure time index (PTI):

PTI is a measure of strength and endurace.

$$\text{PTI} = \left(\frac{\text{mean oesophageal pressure}}{\text{maximum inspiratory pressure}}\right) x \frac{T_i}{T_{tot}}$$

It combines the strength of created pressure with the endurance of Ti/Ttot. Normal value: 0.05-0.12, larger values can predict the onset of respiratory muscle fatigue. PTI>0.15 rules against weaning.

4. Pressure time product (PTP):

PTP estimates oxygen consumption of respiratory muscles and evaluates the patient effort to overcome the mechanical and isometric forces of respiration which consume oxygen without contributing to volume change. It reflects patient effort better than the WOB because it includes the isometric component of muscle pressure and is less influenced by the after-load to contraction. Normal values: 200-300 cmH_2O-s/min in intubated patients and 60-80 cmH_2O-s/min in non-intubated patients.

5. Wave-forms and loops:

As part of the basic recent ventilators; pressure, flow or volume versus time wave-forms can be displayed on a continual basis, as well as the pressure-volume and flow-volume loops. Many or all of these monitoring functions are integrated into the basic ventilator. A ventilator, for example, may display wave-forms but not loops. Information regarding patient effort as patient-ventilator synchrony, auto-PEEP, response to bronchodilator therapy and the work performed by the ventilator can be gained from the analysis of wave-forms and loops even if they are measured internal to the ventilator. However, an accurate reflection of the patient effort through wave-forms and loops are available if data are measured at

the patient airway. On-line side-stream spirometry using a flow-volume monitor provides flow-volume and pressure-volume loops on-line as well as routine spirometric data for detection of pulmonary mechanics [26].

Flow-volume loops result from the simultaneous measurement and plotting of air-flow and lung volumes during a maximal forced expiration. Much of the information from studying forced expiration are obtained from the idealized flow-volume loops (fig. 80).

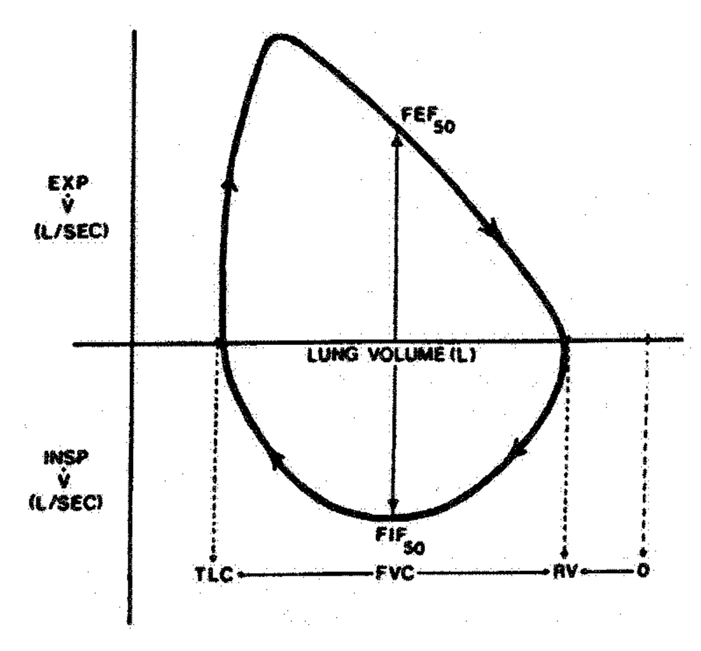


Figure 80: The idealized flow-volume loop

The flow-volume loop can be constructed from routine clinical spirometric data and aids in the anatomic localization of airway obstruction. Forced expiratory and inspiratory flow at 50%

of FVC (FEF_{50} and FIF_{50}) are measured. Note that expiratory flow is represented above the X-axis, whereas inspiratory flow is represented below the axis. In a normal flow-volume loop, the FEF_{50}/FIF_{50} is 1.0 Upper airway lesions as tracheal stenosis are categorized as fixed when there is a plateau during both inspiration and expiration of the flow-volume loop. An extrathoracic obstruction due to a tumour located above the sternal notch, is characterized by a flattening of the flow-volume loop during inspiration. The flattening of the loop represents no further increase in airflow because the mass causes airway collapse. The ratio of FEF_{50}/FIF_{50} is variable but exceeds unity. This is an example of flow-volume loop in restrictive lung disease. An intrathoracic obstruction is characterized by a flattening of the expiratory component of a flow-volume loop but FEF_{50}/FIF_{50} is always below unity. The lesion causes airway collapse during expiration. This is an example of flow-volume loop in obstructive lung disease (fig. 81)

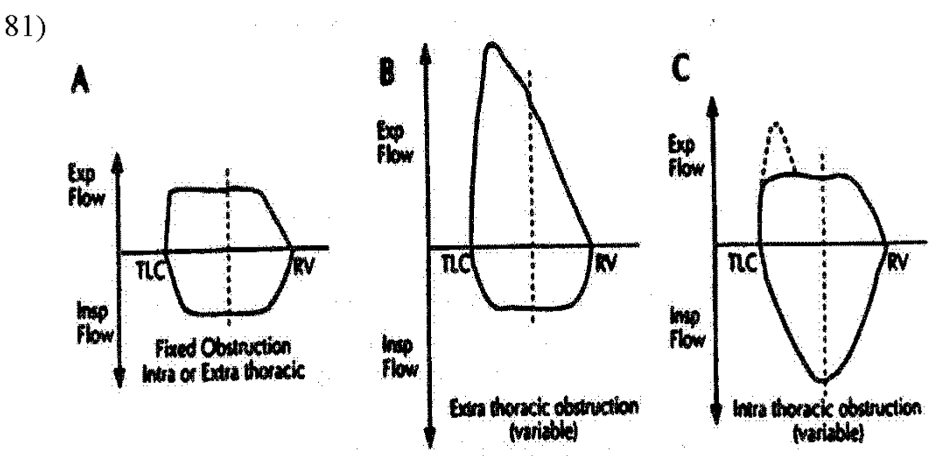


Figure 81: The flow-volume loops in fixed, extrathoracic and intrathoracic airway obstruction.

General anaesthesia in patients with anterior mediastinal mass as lymphoma, thymoma or thyroid retrosternal extension may lead to a potentially catastrophic situation. After induction of anaesthesia, the mass may compress the major vessels, the heart or the tracheobronchial tree producing acute cardiovascular or pulmonary collapse or both. The preoperative evaluation of the flow-volume loops in different positions (sitting and supine) may help to asses potentially obstructive lesions and to identify patients in whom an alternative management be indicated.

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5.1. The feedback concept
5.2. Control of unconsciousness
5.3. Control of muscle relaxation
5.4. Patient-controlled analgesia
5.5. Control strategies
5.6. Applications of controllers
References

5. Class IV Monitors

Monitors of class IV having sensed, collected and organized the data (by a device), interpret them (by a device) and then present the interpreted data to the anaesthetist. They use feedback open or closed loop systems to dose drugs to the patient to maintain desired target values. Devices in this category are likely to increase in number as the uses of microprocessors become more widespread. In spite of this, the data should be supervised by the attending anaesthetist, so that his/her skills may complement those of the controller and monitor.

5.1. The feedback concept:

The major roles performed by the anaesthetist during general anaesthesia are the maintenance of drug-induced unconsciousness, muscle relaxation and analgesia. Each of these roles has been considered in recent years as a possible situation for automated drug administration via feedback strategies.

In the open-loop feedback control system, the anaesthetist feeds the computer software by patient age, weight, temperature and physico-chemical properties of the drug. The computer (controller) uses a variety of mathematical models and equations depending on drug distribution and elimination to predict the desired target value known as the consultative mode, to be achieved by the loop.

The closed feedback loop does not use a mathematical model to predict the target value as the open loop does. However, it has a

set-target-value displayed by the anaesthetist as an input signal to be achieved.

In either open or closed feedback loops, the difference between the input (target or desired) and output (measured) values is treated as an integrated error (E) to be corrected by the controller through changing anaesthetic concentration through a vaporizer or infusion rate through an infusion syringe or pump. This can be compared to an imaginary loop which includes the anaesthetist who corrects the error between the input and output values by manually changing the vaporizer setting or the drug infusion rate (fig. 82).

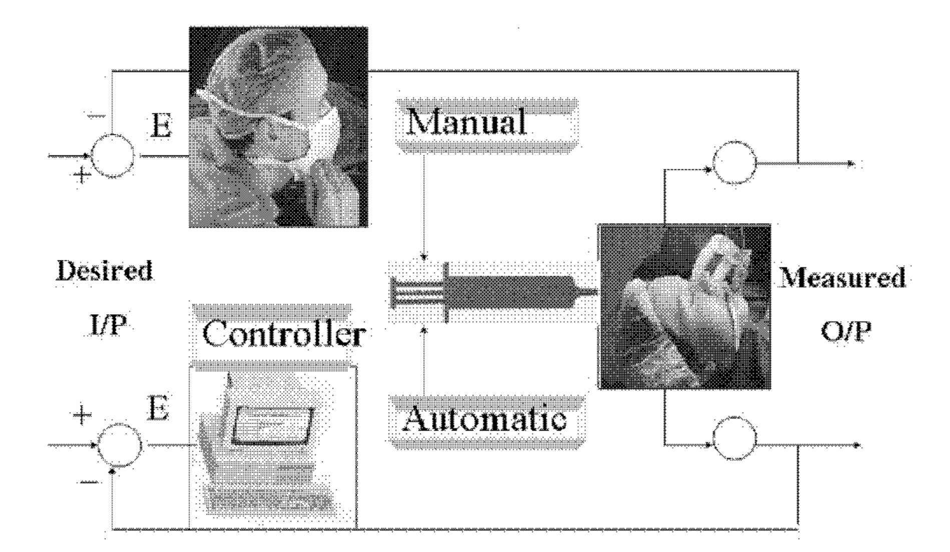


Figure 82: Negative feedback closed loop delivery system, manual versus automatic control.

With the vaporizer, the anaesthetist sets the desired inspired concentration which is then delivered, ideally constant, despite changes in temperature and fresh gas flow. With the control feedback system, the anaesthetist sets the desired brain tension, for example, which would rapidly be achieved by the controller and then maintained constant despite changes in ventilation and cardiac output. Such a control feedback system, would not replace the anaesthetist because s/he is the one who chooses the desired brain tension. In both conditions, the inspired concentration decreases overtime because of the progressively diminishing rate of uptake of the poorly perfused parts of the body.

Of all the potential applications of computer technology to anaesthesia, closed-loop control of physiological functions, which depends on the negative feedback concept, promises the greatest advantage over manual methods. The advantages are most evident in circulatory disturbances where prompt and frequent responses may be required to changing haemodynamics. Short-acting drugs given by infusion are usually selected in these circumstances, and manual titration is often time consuming, tedious and consequently imperfect. Computer control, however, is more responsive, more accurate and less subjective to the human failings of fatigue and inattention.

5.2. Control of unconsciousness:

The anaesthetist mainly aims to control anaesthetic depth and clinical signs are the only widely accepted criteria for its assessment. Anaesthetic depth is usually clinically evaluated by

measuring BP, HR, pupil size and motor activity. Such data included in the Guedel classification were extensively used during the ether era, when anaesthetic depth in the non-paralyzed patient undergoing surgery could be assessed by lack of movement and adequacy of both respiratory and cardiovascular variables.

Recently, measured and desired variables for controlling anaesthetic depth include BP [1], $PETCO_2$ [2], end-tidal anaesthetic agent concentration [3], drug brain anaesthetic concentration [4], evoked responses of various agents [5] including EEG [6] and its BIS modification [7] and auditory evoked potential [8]. Integrated errors between desired and measured values of such variables are corrected by a controller in the open or closed-loop feedback systems. However, up-till-now, there is no absolute or gold standard for the clinical state of anaesthesia against which new methods for measuring its depth can be assessed.

5.2.1. The blood pressure as a target:

Anaesthetists use the BP as the most reliable guide for dosing inhaled or iv anaesthetic agents. To obtain adequate depth of anaesthesia systolic or mean BP has to lie within a predefined range. While this job is manually done by the human anaesthetist, a controller can mimic the control actions of the anaesthetist. A main reason for automating the control of depth of anaesthesia in this way is to release the anaesthetist so that s/he can devote her/his attention to other tasks as controlling fluid balance, ventilation and drug application together with providing adequate anaesthesia with less anaesthetic doses aiming to patient safety and faster recovery.

The controller uses the error between a desired and a measured value of BP for guiding anaesthetic doses to correct this error. Keeping the BP around a defined desired value, the controller is more superior to an ordinary human controller [1]. (fig. 83)

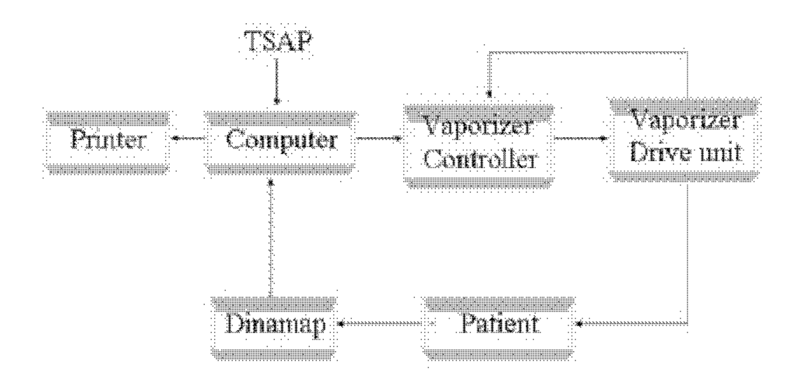


Figure 83:Components of the feed-back control system

An argument against this practice is that BP depends on other factors as blood volume and cardiovascular function. However, when the anaesthetist encounters hypo-or hypervolaemia or heart failure, s/he always adjusts the anaesthetic concentration to rapidly bring BP to normal before treating the primary cause. This is because the actual control value is the SVR, and the adjustment value is the drug inducible tone of the arterial musculature. This is achieved through an afterload controller (fig. 84).

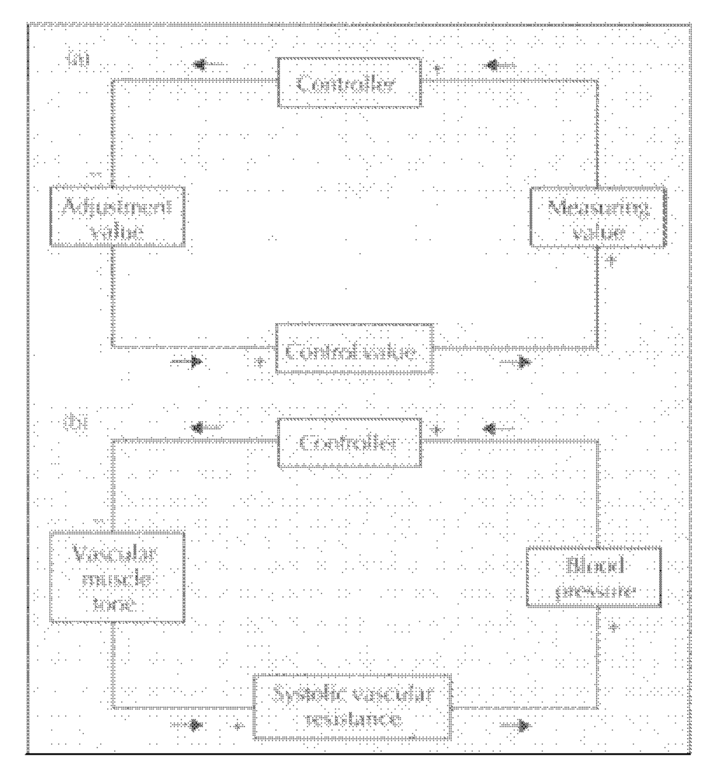


Figure 84: (a) the principal signal flow and its effect in a closed-loop control system and (b) a controller for blood-pressure control.

Meier et al [1] used a closed loop to achieve a target systolic BP by isoflurane. In their feedback system, the controller suggests a consultative mode for an isoflurane concentration to achieve the target. If the end-tidal isoflurane concentration is <0.4%, the controller increases the anaesthetic concentration by 0.1% for 3 min and repeats the measurement. If the end-tidal isoflurane concentration is >2.5%, the controller decreases the anaesthetic concentration by 0.2% and the controller turns off. When the end-

tidal concentration is between 0.4% and 2.5%, the controller starts again. The anaesthetist can interfere at any time by manual control.

Mean percentage error

30

20

10

0

0 1 2 3 4 5 6 7 8 9 10 11 12

Manual

Automatic

Time frames (10 min intervals)

Figure 85: Reduction in error of mean arterial blood pressure over time: manual versus automatic control [1].

An advantage of Meier et al [1] model is that the controller is first tested in the so-called consultative mode which means that the controller suggests a value for isoflurane inflow concentration, and the anaesthetist can then decide to set this value or not. Patient safety is thus assured in an early stage of surgery. Analysis of data collected during surgery showed that the suggested isoflurane consultative mode concentration was always very close to the actual concentration set by the anaesthetist. Therefore, a fully automatic run is completed during which the controller actually sets the isoflurane concentration administered to the patient. Modelling the relationship between isoflurance concentration and BP proved the

high quality of controller design and implementation. It proved that the controller does a good job of keeping BP constant when compared to the human anaesthetist doing the same job. (fig. 85)

A closed system of infusion control using a microcomputer, has been successfully used in clinical practice with sodium nitroprusside and trinitroglycerine to control the BP during and after cardiac surgery. The signal from an indwelling arterial cannula is taken from the monitor through an analogue/digital converter to a microcomputer. Infusion rates of drugs are calculated and communicated to a volumetric infusion pump to the patient to correct the error between the input and output signals (fig. 86).

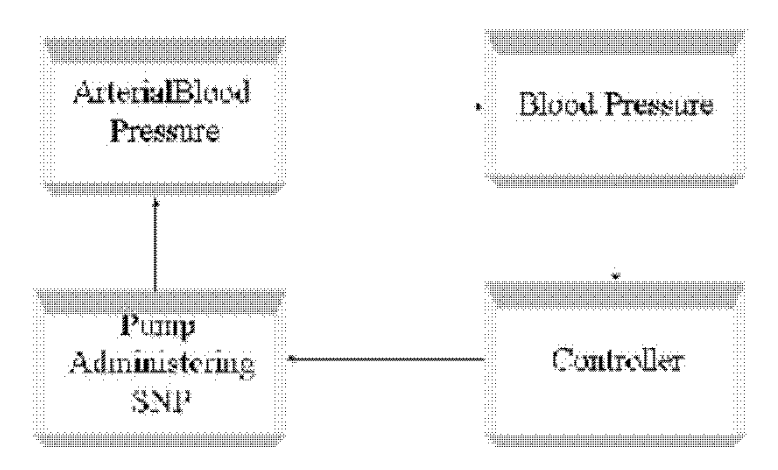


Figure 86: Feedback system to control blood pressure by administration of sodium nitroprusside

5.2.2. Brain anaesthetic tension as a target:

Chilcoat et al [4] designed a negative feedback loop for controlling anaesthetic depth by an inhalational anaesthetic agent (fig. 87). The anaesthetist sets the N_2O and O_2 flowmeters in the ordinary way, then s/he sets the required brain tension of the inhalational agent on the controller in the form of minimal anaesthetic concentration (MAC) value. The system computes the resulting brain tension of N_2O and then the inspired concentration of the volatile agent needed to achieve the required total brain tension. This concentration is then set automatically on a vaporizer and the resulting mixture is delivered to the patient via a ventilator with a non-rebreathing anaesthetic system.

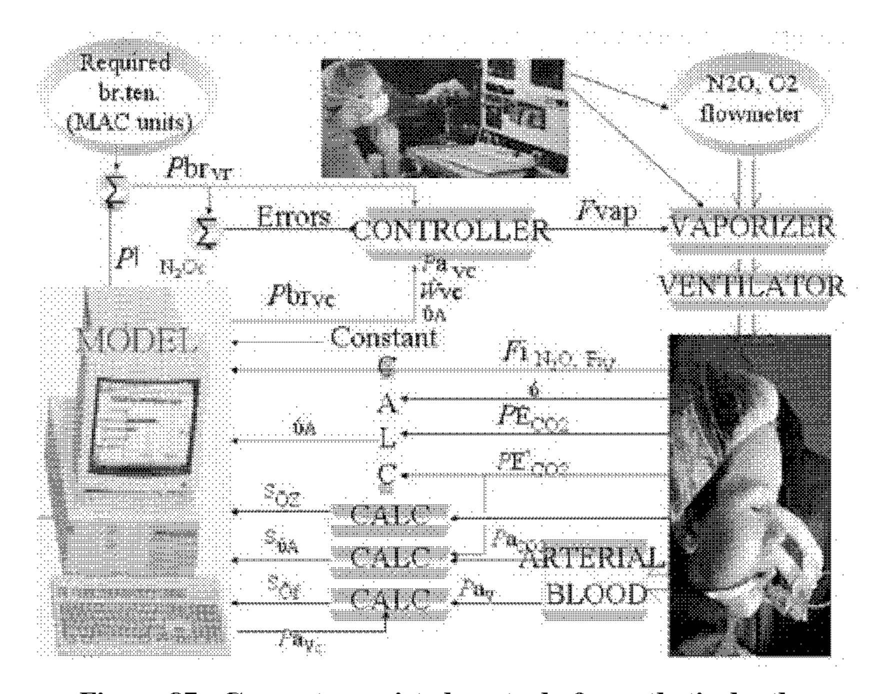


Figure 87 : Computer assisted control of anaethetic depth.

Alveolar ventilation is obtained from measurements of total ventilation and of the inspired, mixed-expired and end-tidal concentration of CO_2. Cardiac output is assumed to be normal before the start of the anaesthetic and to change in accordance with computed brain tension. Occasionally, a sample of arterial blood is taken and analyzed for $PaCO_2$ to permit improved estimate of alveolar ventilation.

The overall operation of the system is summarized diagrammatically in figure (87). Before induction, the system is provided with values for body mass, blood/gas partition coefficient for halothane at 37°C, body temperature, ambient temperature and barometric pressure. These are constants entering the model. At induction, the anaesthetist sets the flows of N_2O and O_2 in the usual way, but s/he then sets the required or total brain tension of the inhalational anaesthetic agent in MAC units.

There is a basic 10 second cycle of the operation. At the start of each cycle, the system computes the current model brain tension of N_2O in MAC units ($PbrN_2Oc$) and substracts this from the required total tension to yield the required brain tension of halothane (Pbr_{vr}). The difference quantifies a set equation (the controller) which defines the vaporizer concentration required (Fvapr) to bring the model brain tension to the required value as quickly as possible. This concentration is then automatically set on the vaporizer and is delivered, together with N_2O and O_2, via a ventilator, to the patient for the coming 10-second period.

Initially, the cardiac output is assumed to be 0.1L/min/kg. Every 10-minutes, an electrical-impedence estimate (Qz) of cardiac

output is made. Every 30 minutes $PaCO_2$ is divided by $PETCO_2$ to obtain a measured alveolar-ventilation scaling factor (SVA). The measured arterial halothane tension (Pav) is used as feedback to correct any errors in the model. A third cardiac output scaling factor (SQf) is calculated and applied to previous computations, leading to renewed activity in the controller and vaporizer to bring more accurately computed brain tension to the required value.

So, all what is needed is to start the control program with initial data as barometric pressure, body mass, body temperature and blood/gas partition coefficient for N_2O and halothane. A preliminary cardiac output and minute ventilation are obtained and then the desired brain tension is set by the control knob to the required value after setting the inspired N_2O/O_2 mixture values. The computer processes all measurements of concentration, ventilation and cardiac output. A plastic potentiometer mounted under the knob senses its position and changes the vaporizer setting as ordered by the controller.

5.2.3. End-tidal carbon dioxide tension as a target:

During general anaesthesia, ventilation may be controlled continuously and adjusted in order to maintain a suitable CO_2 tension. Monitoring the $PETCO_2$ allows indirect, non-invasive, breath-by-breath estimate of arterial CO_2 tension and is therefore essential for the control of the patient under mechanical ventilation (fig. 88). As CO_2 production per minute and the relation of alveolar ventilation to perfusion (V/Q) may change during anaesthesia and surgery, adjustment of the ventilator settings by the anaesthetist is

required. Alternatively, automatic closed-loop, based on the negative feedback control of $PETCO_2$, can control mechanical ventilation [1]. The most frequently used output variables of these controllers are the ventilator settings for frequency, tidal volume and respiratory minute volume, but other variables as the inspired/expired ratio may be adjusted. In addition, CO_2 may be delivered from a rebreathing bag and added to the inspiratory fresh gas mixture to maintain a targeted $PETCO_2$. It could be concluded that control techniques depend on modern feedback control systems and are very promising as future techniques for controlled anaesthesia.

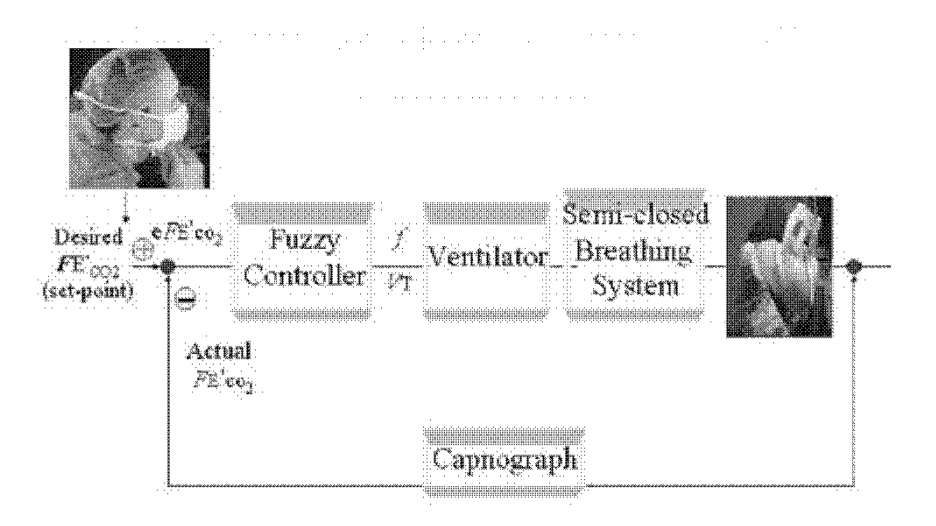


Figure 88: Control loop for mechanical ventilation using capnography

5.2.4. End-tidal anaesthetic concentration as a target:

Curatolo et al [9] and Lockwood et al [10] developed computer-controlled closed-loop breathing systems which rapidly achieve and maintain prescribed end-tidal isoflurane in O_2 concentrations. Ross et al [3] used a model in which the needed inhalational anaesthetic agent was injected as a liquid in the inspired limb of the breathing circuit. El-Attar [11] and Weir and Kennedy [12] observed that dosing of the drug at intervals produces fluctuating circuit concentrations which could be overcome by using a continuous infusion of the liquid anaesthetic in the breathing system (fig. 89). They claimed that this technique is also useful for producing deliberate hypotension by isoflurane.

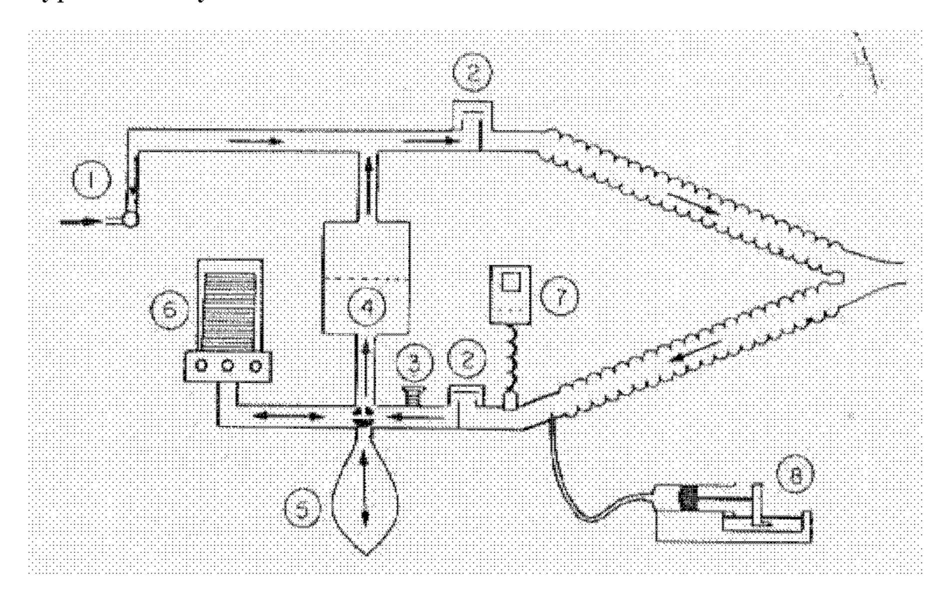


Figure 89 : Feed-back control using liquid isoflurane in the breathing circuit 1. Oxygen flowmeter; 2. Unidirectional valves; 3. Pop-off valve; 4. Soda lime canister; 5. Reservoir bag; 6. Bellows ventilator; 7. Oxygen analyzer; 8. Syringe pump.

5.2.5. Evoked responses as a target:

Evoked responses are derived from the EEG in response to auditory, somatosensory, nociceptive and visual stimuli. These responses are obvious candidates for investigation as they reflect the functional integrity of specific peripheral and CNS regions in humans. The changes that occur in the evoked responses allow anaesthetists to assess the effects of drugs that they are administering on the brain as a target site. Consequently, speciality areas of general anaesthesia, intensive care and pain assessment developed interest in evoked response monitoring.

A system that can be used to record an evoked response includes a personal computer fitted into a monitoring device [5]. The EEG is recorded from scalp electrodes, amplified and relayed to the computer. The pre-amplifier produces a stimulus (e.g. auditory) which is applied to the patients' ears via miniature earpieces. Software installed on the computer analyses the EEG with respect to the stimulus to produce an averaged evoked response, which is constantly updated and displayed on the screen. In the case of the brain-stem auditory evoked response (BAER), the electrical potential is recorded from an electrode placed on the centre of the top of the head as a reference electrode which is subtracted from that recorded from an electrode placed over the temporal lobe on the mastoid process as the active electrode. BAER is best evoked by clicks of short duration (100-500ms). A certain level of stimulus intensity is required to elicit a response.

To date BAER is most promising for distinguishing a patient who is aware from one who is anaesthetized. So, BAER is a suitable

basis to detect intraoperative awareness as indicated by the patient's ability to register sound. If intraoperative awareness includes subsequent memory (implicit or explicit), then the situation becomes more complicated because of the amnesic drugs used during general anaesthesia.

A feedback closed loop system based on BAER index has been developed with the administration of propofol [13]. The BAER index is entered into a controller, which calculates the target blood concentration of propofol needed to maintain the BAER index at a desired value. Propofol is infused guided by the controller.

The BAER closed-loop is currently the only system that operates satisfactorily in non-paralyzed patients breathing spontaneously [8].

In the same-way an EEG feedback control system was used for successful administration of alfentanil / NO_2 anaesthesia without awareness [6]. However, due to the cumbersome attachments of the EEG and the experience needed for its interpretation, many trials have been carried out for EEG modification aiming to simpler use in clinical practice.

In October 1996, the Bispectral Index (BIS) achieved approval by the Food and Drug Administration as the first EEG-based monitor of anaesthetic depth[14]. An adequate level of anaesthesia is achieved with BIS of 40-60 [15]. A closed loop for anaesthetic depth including BIS as a monitor indicated that a BIS level of 40 reflects deep anaesthesia, a level of 50 reflects adequate anaesthesia. A level above 60 was expected to reflect light anaesthesia with the patient experiencing intraoperative awareness [7]

BIS-guided reduction of anaesthetic medication saved costs and did not increase the risk of intraoperative awareness [7]. However, total costs were increased by monitoring BIS, because of the price of the BIS electrodes. It has been also shown that doses of sufentanil and midazolam were adjusted to achieve a BIS level of 40-50 in patients undergoing coronary artery bypass grafting, where, BIS guided reduction of anaesthetic medications was possible without explicit intraoperative recalling [16,17].

5.2.6. Total intravenous anaesthesia as a target:

Conventional use of total intravenous anaesthesia (TIVA) depends, mostly, on manually adjusted step-down manner to achieve and maintain a constant therapeutic blood concentration varying according to the use and doses of supplementary agents and the nature of surgery. In a healthy adult these values are 10mg/kg/hr for 10 min, 8mg/kg/hr for the next 10 min and a maintenance dose of 6mg/kg/hr.

The computer-controlled infusion regimen controls the infusion rate automatically on the basis of propofol pharmacokinetic data and patient data to achieve and maintain the therapeutic blood propofol concentration [13]. An increase in propofol concentration is achieved by rapid fixed infusion rate decided by the controller until the new blood level is reached. A decrease in drug concentration is achieved by discontinuing the infusion till the selected blood concentration is obtained. There is a linear relationship between the infusion rate and the resulting steady state blood propofol concentration. So, the use of this system to manipulate blood propofol concentration is similar to the use of a vaporizer with an

inhalation anaesthetic agent. The same system can be used as an adjuvant to spinal anaesthesia to provide propofol hypnosis by a blood concentration of 0.5-2.5 μg/ml.

5.3. Control of muscle relaxation:

During general anaesthesia, it is not the problem of controlled ventilation, but the problem of drug induced relaxation which counts. (fig. 90) The problem is how the drug is given and titrated according to surgical needs and how to ensure more safe recovery, without over-dosage or recurarization.

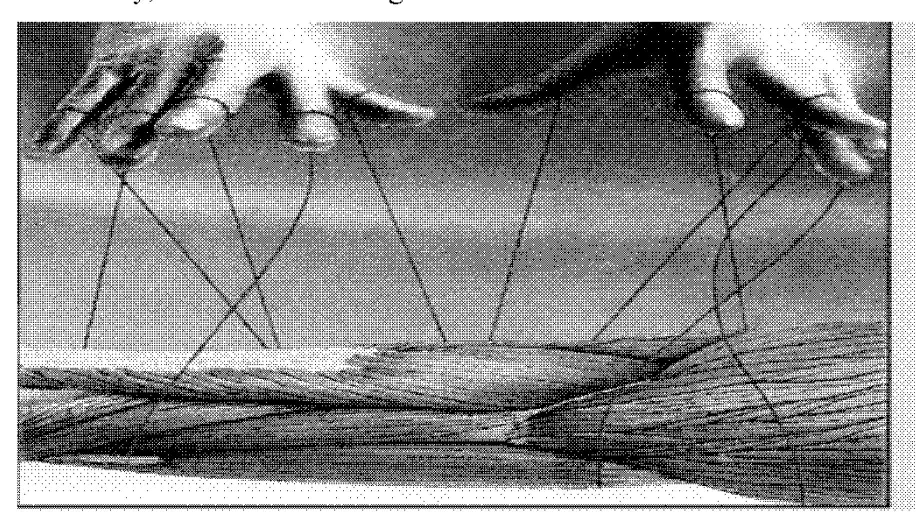


Figure 90: The art of controlling muscle relaxation.

A closed-loop for muscle relaxation includes a microcomputer, a neuromuscular monitor, a volumetric infusion device and the patient. Early work was done on sheep [18] and humans[19,20]. Wait et al [21] used a Datex relaxograph, a controller mathematical model based on patient and drug data, a syringe driver

and iv line fixed to the patient. (fig. 91) A rough estimate of the neuromuscular block, through the closed loop, was done through iv administration of a bolus dose of tracrium at the beginning of the operation. This bolus dose provides a fast relaxation to enable the surgeon to start the operation. This dose is a rough estimate for the sensitivity response of the human muscle to the relaxant drug, as it is non-ethical to estimate drug sensitivity on the human. The response of the dose is divided into three bands, high, medium and low. Accordingly, muscle relaxation is maintained by the controller calculating the drug infusion rate (ml/hr) to achieve a target T_1%. The relaxograph shows T_4/T_1 and gives an analogue signal proportional to the level of the relaxant drug. The signal is the basis of on-line intelligent control. Drug infusion is stopped 10 min before the end of surgery and reversal of relaxation is achieved by neostigmine – atropine using a nerve stimulator.

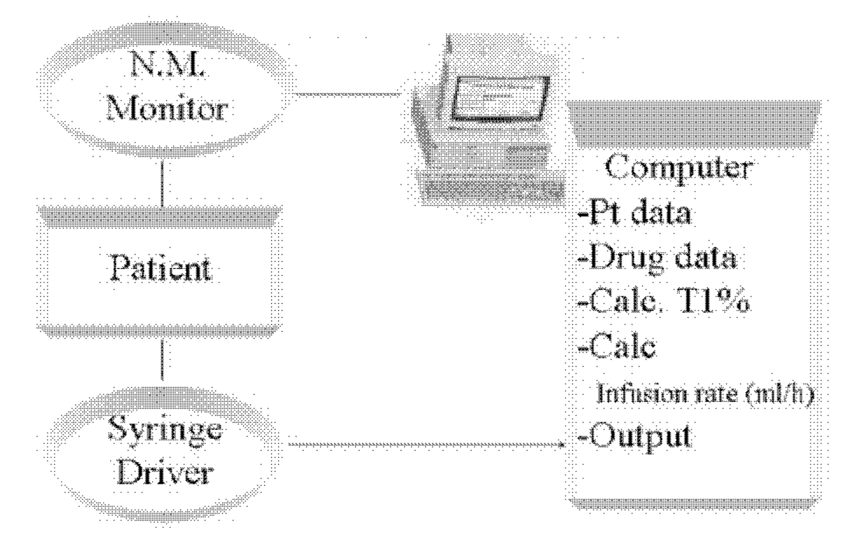


Figure 91 :Closed loop control of muscle relaxation

5.4. Patient controlled Analgesia:

In considering possible ways of improving the drug treatment of acute pain, Norman [22] suggested that six questions should be asked about the system to be used to deliver analgesia:

1) who selects the drug to be used ?
2) who decides the dose ?
3) who decides when the drug should be given ?
4) who decides when more drug is necessary ?
5) who assesses the efficacy of the treatment ?
6) who assesses the dangers ?

In most instances, the doctor selects the drug from a range approved by the appropriate authorities and then decides the dose and times for remedication; the nurse may decide when the first dose is necessary and usually decides when subsequent doses are necessary. Deciding who is to assess the efficacy of the regimen, however, is more difficult. The nurse can only administer a drug ordered by the doctor .On the basis of perceived dangers , inefficacious dosage regimens are frequently ordered and / or administered.[23] Therefore , in answer to the question 'who is in control of the drug delivery system ?', Norman [22] proposed that the logical choice was the patient – not the medical or nursing staff . Such patient – controlled analgesia (PCA) methods appear to have been remarkably successful. [24]

There are four basic variants of PCA. Bolus demand: demands of a fixed bolus dose are made to fixed maximum amount and fixed maximum rate, this is the most commonly used system.

Infusion - demand : demands are administered as an infusion. Bolus demand and constant infusion: demand bolus doses supplement a background infusion; this is a commonly used system . Bolus demand and variable infusion: a delivery system – based microprocessor monitors the demand rate and adapts the background infusion accordingly.

There are also four basic variables within a PCA system: the drug choice, the incremental dose per demand, the maximum dose (or dose rate) , and the lockout interval between demands .

Attempts to improve opioid dosage regimens have been based on the pharmacokinetic and pharmacodynamic characteristics of the drugs to be used [23-27]. It has been proposed that there is a continuous relationship between opioid agonist blood concentration and response, that there is a minimum blood concentration associated with effective analgesia (MEAC) and that pharmacokinetic techniques can be applied to design dosage regimens to achieve the target blood drug concentration [26,27] However , it has been pointed out that the limitations of pharmacokinetically designed dosage regimens of analgesics are largely related to blood concentration – effect relationship [24]. The rational treatment of pain with all of its attendant physical, biochemical, physiological, psychological and sociological variables may have a different basis to other forms of drug treatment and thus predetermined individualisation of dosage is extremely difficult.

Opioid or local anaesthetic administration is intended to achieve a minimum effective (analgesic) concentration of the drug in blood (MEAC) without producing side effects. Since this MEAC

varies greatly between patients, its achievement and maintenance should be guided more by individual titration to response than by recipes based upon published pharmacokinetics. These reflect drug blood concentrations in samples of populations without necessarily being able to reflect drug effects in the individual patients being treated. [28] Unfortunately the MEAC determined under specific conditions is not necessarily constant and may, for example, be increased by movement or physiotherapy or decreased by distraction.

The incremental dose of any drug chosen for PCA depends on the potency of the chosen drug. In a systematic comparison of the different drugs, the physicochemical properties are a logical starting point. All of the currently used pure opioid agonists are basic amines and, except for morphine, are lipophilic molecules; morphine is more hydrophilic. It is generally believed that the unbound, non-ionised form of the drug is free to cross membranes in the body, that is done at rates which parallel the lipid solubilities of the agents.

Differences in drug potency are also determined by differences in the affinity of the various substances for the receptors. These values are usually determined by competitive displacement analysis. While fentanyl is approximately 200 times more potent than morphine in analgesic bioassays, its mu – receptor binding affinity in vitro is less than 10 times that of morphine [29] Conversely, the potency of pethidine in various analgesic bioassays is between 10 and 25% that of morphine but its mu – receptor binding affinity is only approximately 2% that of morphine [30] .This is rationalized

on the basis that the greater lipid solubility of fentanyl and pethidine allows them greater access to the receptors than morphine and that this tends to offset the apparent disparity between receptor affinity and potency .

Patient controlled epidural analgesia (PCEA) with pethidine may be preferable to other epidural opioids because pethidine has intrinsic local anaesthetic activity and intermediate lipid solubility[31]. Epidural analgesia using local anaesthetic combined with opioid may show synergism[32] and provide superior analgesia during activity[33] compared with systemic opioids. It has recently been shown that PCEA with pethidine 4 mg/ml or ropivacaine 0.2% with fentanyl 2 mcg/ml produced similar analgesia and side-effects in postoperative general surgical and orthopaedic patients[34].

Patient controlled analgesia denotes self-administration of small doses of narcotics by the patient when s/he experiences pain, to minimize the effects of pharmacokinetic and pharmacodynamic variabilities among individuals [35]. Iv opioid infusions are becoming increasingly used to cover background pain. Incident pain occurs with movement, dressings or physiotherapy and needs to be covered. This is achieved through an iv PCA device which consists of a microprocessor-controlled drug infusion pump or syringe triggered by depressing a button by the patient anticipating pain. (fig. 92)

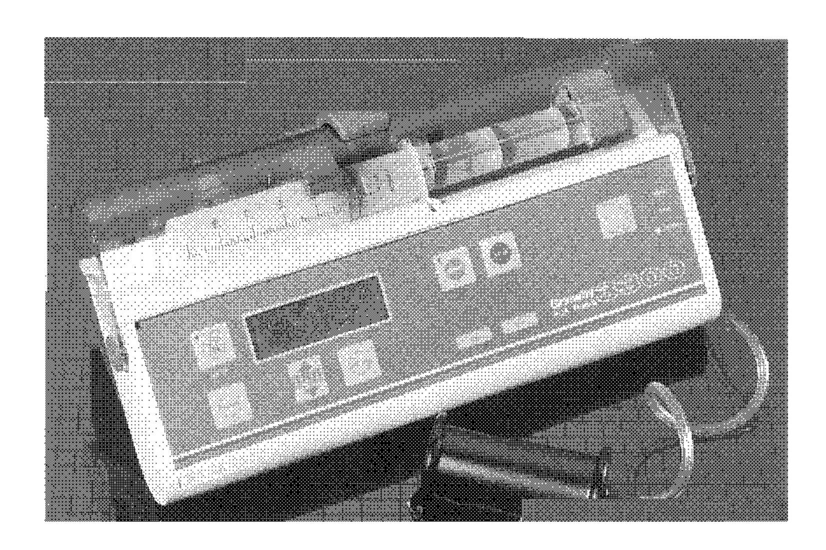


Figure 92: The infusion syringe for patient-controlled analgesia.

PCA approach is based on the premise that a negative feedback open-loop exists. When pain is reduced or disappears, there will be no further demand of analgesics until it returns, the patient providing the input signal for pain control.

The system usually consists of a sophisticated infusion device which allows on-demand bolus injection of the drug, with or without continuous background infusion. The size and rate of the bolus dose may be altered. Inadvertent over-dosage is avoided by limiting the size of individual boluses and the total dose administered within a set-period. The minimal time between boluses can also be pre-set (lock-out interval). The controls must be inaccessible to the patient or the relatives.

PCA has been shown to provide more consistent plasma drug levels when compared with standard im techniques, with less

complications and reduced total drug dosage. Drugs with relatively short half-lives are usually used. However, patients require adequate monitoring since respiratory depression may still occur. The technique has been also used with extradural analgesia in the postoprative period.

In hospital, parturients experience a loss of control, to some extent, in privacy, mobility, bodily functions, and choice. With the advent of PCA some control has been returned to patients who have increased their satisfaction with pain relief. Some studies have shown that application of PCA to epidural analgesia in labour allows parturients to titrate adequate and satisfactory analgesic levels on demand [36-40]. Self-administration of small increments of dilute local anaethetic is more likely to avoid the adverse consequences of large bolus administration .

Patient – controlled epidural analgesia (PCEA) is effective and associated with high patient satisfaction [36]. In addition, it is safe and is associated with lower local anaesthetic requirments than continuous infusion epidural analgesia (CIEA). PCEA is also used for management of postoperative pain in the same way as patient – controlled intravenous ansesthesia (PCIA) is used.

Regarding the disadvantages of PCA, the cost of the device, the programming errors and device malfunction represent major drawbacks of its use. The technique is also difficult to use by young children and by mentally handicapped adults .The side-effects of the analgesic drugs are still possibly recorded as respiratory depression , vomiting , pruritis and urinany retension.

Recently, a new adaptive system has been designed to improve PCA through the use of a variable bolus dose and a variable background infusion of analgesic (fig. 93). A novel hand-set allows patients to rate their own pain on a linear scale of 1 to 10. Data derived from the hand-set signals are used by an expert algorithm to repeatedly adapt the drug dosage of the bolus and of the background infusion according to both current pain intensity and the patient's response to previous dosage. This computer-controlled or "smart" PCA rapidly learns the patient's individual needs and provides continuously tailored pain relief. [41]

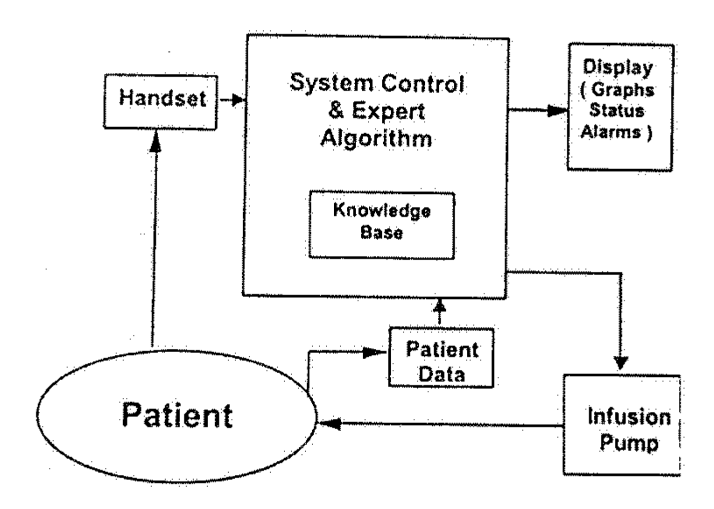


Figure 93: The adaptive patient-controlled analgesia system

PCA offers something more than just morphine. It offers the patient the security of knowing that s/he has some control over his/her pain. Also, PCA guarantees that the patient is checked every

hour, and if pain is not under control, his/her nurse has immediate access to the Acute Pain Service (APS) [42].

According to the International Association for the Study of Pain (IASP), APS is "an inhospital organization which ensures optimal pain management for every patient who undergoes surgery including children and those undergoing surgery on ambulatory basis" [(42).] It is becoming increasingly clear that the solution to the problem of postoperative pain management lies not so much in the development of new techniques as in the development of an organization to exploit existing expertise which is based on team approach [(43).] This is one of the main conclusions and recommendations of interdisciplinary expert committee reports by National Health and Medical Research Council of Australia, Royal College of Surgeons of England and the College of Anaesthetists, U.S. Department of Health and Human Services, and the IASP.

A postoperative pain management organization has been developing slowly in USA [44]. The organization is anaesthesia-based because of the needed experience to provide high quality analgesia by using high-technology pain management services, namely; epidural and intravenous patient controlled analgesia. Therefore, the American Society of Anaesthesiologists (ASA), [45], recommended the anaesthesiologists' leadership of the APS organization for integrating pain management practices into the various aspects of perioperative care.

Several studies on the quality of postoperative pain management, that utilized the American style of APS have been reported [46-50]. Miaskowski et al [51] in 1999 utilized a standardized

approach to compare the quality of pain service to patients who were and who were not cared for by anaesthesia-based pain service. Out of a total of 5837 patients, 49% were cared for by anaesthesiologist- based pain service. Patients who received pain service by anaesthesiologists were significantly more satisfied and reported significantly lower levels and intensity of pain in the postoperative period, with less pruritis, sedation or nausea, and were discharged sooner from the hospital. The findings from this study demonstrated that the provided care had a significant impact on patient outcome. The costs of USA-style APS were very high accounting for $100-$300 per patient [42, 43].

For financial reasons, many countries restrained the American style of APS. The European style of APS, encourages a nurse-based-anaesthesiologist-supervised approach. A specially trained Acute Pain Nurse (APN) makes daily rounds of all surgery departments. She checks visual analogue scale (VAS) recordings on charts, solves trouble-shooting technical difficulties and transfers problem patients to acute pain anaesthesiologists. Day and night nurses are responsible for implementation of pain management guidelines and monitoring routines on the ward. Encouraging the Europeans-style and criticising the USA-style of APS, Bridenbaugh [42] reported that the function of the anaesthesiologist should not be to run around the hospital filling up epidural catheters with various analgesic mixtures or setting infusion pumps, and that it would be far better for his/her time to be used in teaching or performing nerve blocks.

After the publication of a report by a joint working party of Royal College of Surgeons and College of Anaesthetists in 1990, there has been considerable interest in improving postoperative pain relief in the UK [43]. This has centered around the development of High Dependency Units (HDU's), Acute Pain Teams (APT's) and expansion in the use of techniques such as PCA. [43]

So, by the start of the third millenium, much remains to be done to design an appropriate approach regimens for APS in developing countries like Egypt, with a sound scientific foundation. A suggested Egyptian APS model has been recently suggested [52]. The model encourges prevention of pain and stress by proper preparation and patient premedication, and pre-empting of pain by local analgesics, parenteral opioids or NSAID’s with specific cases left to be managed by PCA.

Such a suggested Egyptian organization model may open the door to other Middle-east and African pain authorities to introduce their own organization models. Guided by the IASP, the interaction of these models might push to light an African and Middle-east style for APS side-by-side with the American and European styles. The importance of different styles of APS has been recently confirmed by the Society of Paediatric Anesthesia at its 15th annual meeting at New Orleans, Louisiana which clearly defined the alleviation of pain as "a basic human right" irrespective of age, medical condition, treatment, primary service response for the patient care or medical institution[53].

5.5. Control strategies:

Control strategies for a managed process (anaesthetic, analgesic, relaxant or therapeutic) may be simple, adaptive or intelligent.

5.5.1. Simple control strategies:

An error between the measured and desired values of a chosen variable, is mostly corrected by a simple PID controller, where an integrated error acts as a performance index. PID as abbreviations stand for Proportional Integral Differential. Proportional means that the controller output is proportional to the input value. Integral means that the response to error increases so long as the error is present. Differential or Derivative means that the controller can anticipate the trend error and achieve its correction. Correction of the calculated error is achieved through automatically and repeatedly changing the vaporizer setting or the device infusion rate.

The controller algorithm directs the computer to receive a measured signal every 10-20 seconds and updates proper output values. In addition to the PID controller, simple control strategies include PI, PD or P controllers.

Brown et al [19] included PID controller in a negative feedback closed-loop system for muscle relaxation with good results. Wait et al [21] added a relay to the output of a Datex relaxograph alarm indicator and 50% more relaxant drug was consumed than by using a classical PI controller.

Robb et al [42] described a closed-loop including PI controller for major surgery under enflurane anaesthesia. The system automatically adjusted enflurane concentration according to the

desired systolic BP. Additional morphine was administered if the demand for enflurane exceeded a preset value. Satisfactory control of systolic BP was achieved and anaesthesia was clinically adequate with no reported awareness. Anaesthetic adequacy was clinically assessed at 5 min intervals using the PRST score [54]. This score is the sum of individual scores for systolic Pressure, heart Rate, Sweating and Tears. Each individual score has a value of 0, 1 or 2 with a possible range for the PRST score of 0-8. A total score of 0-4 during general anaesthesia indicates an acceptable level of anaesthetic depth. This approach has some similarities with the intelligent controller described later.

The first limitation of PI controllers and other simple controllers is that they cannot anticipate the surgical stimulus. For this reason, Robb et al [42] administered a background concentration of 0.6% enflurane for 10 min to provide adequate anaesthesia at the start of surgery. In addition, the controller ordered iv boluses of 0.05 mg/kg morphine whenever the sum of 5 vaporizer settings exceeded 15% of the desired output value. Occurrence of oscillations represented a second limitation to simple controllers. As deviations from the desired value are over-compensated owing to the delayed onset of action, the controller tends to oscillate and the deviation over a certain period is integrated. These two limitations led to the need to investigate advanced controllers for self-adaptive and later intelligent self-organizing control strategies [55].

A negative feedback closed-loop for insulin delivery for diabetes control included a controller of the PD type to measure changing glucose level and its changing rate [56]. It is evident that in

simple control strategies, the goals of the controller are fixed and defined by the designer. Goals cannot be achieved by recognition of the situation (perception) and utilizing a background knowledge (experience). This led to the evolution of advanced control strategies (adaptive and intelligent) that can benefit from advances in artificial neural network as a tool for on-line learning. Thus, a neural controller has been obtained using a knowledge-base as a data generator with input variables. Similarly, a patient model was planned as a simulator for validation of the neural controller [55].

5.5.2. Adaptive control strategies:

The previously described simple control strategies calculate the error between the desired and measured signals according to a mathematical formula through a single-input single-output control concept [1]. Due to enormous patient to patient variations in dynamic parameters, it is always difficult to design a fixed simple controller suitable for all patients [55]. This has led to the evolution of adaptive control strategies with adapted mathematical models according to the changing process. Adaptive controllers provide more accurate adjustment by adapting the constants during regulation. This is done by making use of the initial response of the system. This method takes into accounte the individual responsiveness of a patient to the administered drug and the changing responsiveness during its administration. Millard et al [57] have used adaptive control of isoflurane for deliberate hypotension to facilitate ear, nose and throat (ENT) surgery.

One way of optimising self-adaptive control is to include an estimator in addition to the controller in the closed loop in order to estimate the mathematical model process to help to achieve the desired output value quickly [58] (fig. 94). The estimator provides a suitable model for the changing process and gives the suitable output to the controller. In this way, the adaptive controller would work with a better model instead of working by trial and error [59]. Tatnall et al [60] described an online feedback strategy for control of minimal anaesthetic concentration (MAC), using an initial parameter estimator working on the first few breaths.

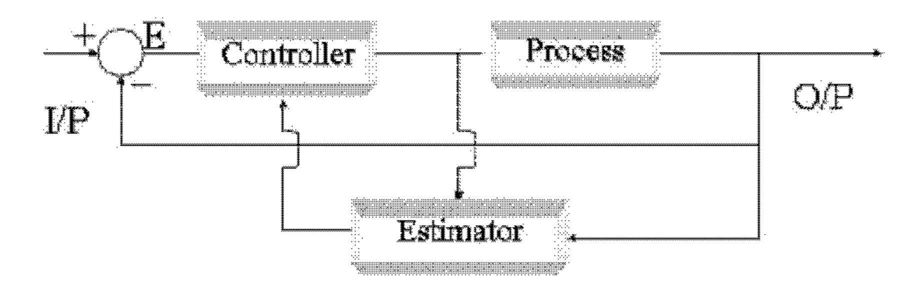


Figure 94 :Optimum contoller for adaptive control strategies using an estmiator.

Another way of optimising self-adaptive control is to optimize error correction processing quickly between measured and desired values. This is achieved by using more than one controller. Linkens et al [61] used two controllers to offset the time delay inherent in the drug circulation. Again, a comparator can give a chance for the choice of the suitable controller for processing and achieving optimum control of the process (fig. 95).

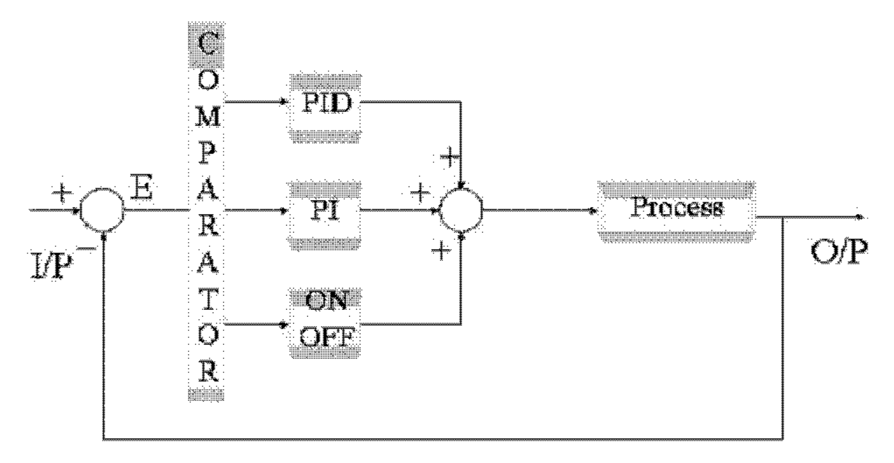


Figure 95: Optimum Controller for adaptive control for strategies using a comparator.

Ritchie et al [62] utilized four PI controllers to regulate closed circuit anaesthetic agent delivery. The first PI controller adjusted the total fresh gas flow of N_2O and oxygen in order to regulate the circuit volume. The second PI controller adjusted the ratio of oxygen flow to total flow in order to regulate the circuit oxygen concentration. The third PI controller regulated the end-tidal anaesthetic concentration, while the fourth PI controller adjusted the minute volume to regulate $PETCO_2$. It was noted that a dual mode controller was required to control both induction and regulation phases and that artifacts were common place making intelligent alarm handling necessary.

It is evident that self-adaptive control strategies could expand the concept of automation. Coupled with advances in microprocessor technology, automation has been brought to different levels of application. So, adaptive controllers could solve problems with predefined fixed goals, through incorporating

modelling, analysis, simulation, design, implementation and verification in the control system.

5.5.3. Intelligent control strategies:

Intelligent control strategies keep an output value in memory to predict the following output value according to history (on-line learning). Figure (96) shows a multivariable controller with two input and two output values [63]. Each input initiates a controller affecting two processes manipulating the two outlet values. Based on this simplified example, there has recently been a great deal of interest among research workers in the design and theory of non-linear multivariable controllers. This is the basis of multi-input multi-output (MIMO) intelligent control systems.

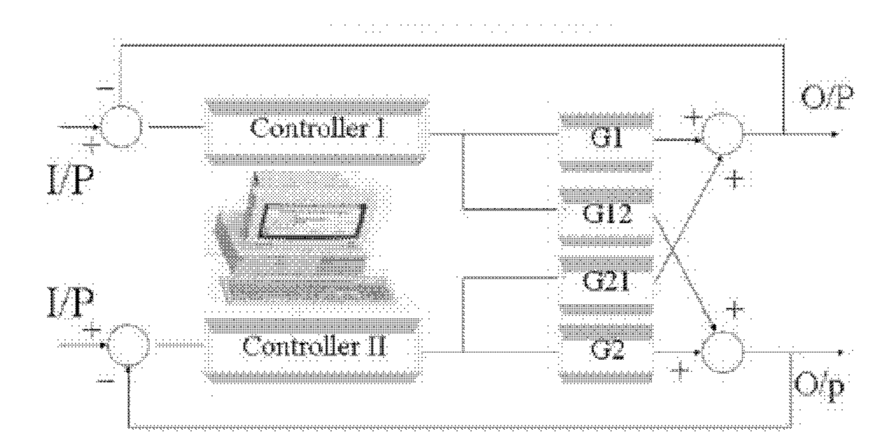


Figure 96: Control for multivariable anaesthesia.

Control strategies for multivariable anaesthesia considered the simultaneous control of unconsciousness and muscle relaxation by Linkens et al [63]. A simplified 2-input / 2-output model has been elicited for merged infusion of isoflurane and atracurium to humans. A similar model has been obtained for enflurane and pancuronium given to dogs. The models in either situation used the mean BP as an indicator of anaesthetic depth and evoked EMG as an indicator of muscle relaxation. Linkens et al [63] have applied adaptive and intelligent control strategies to the just-mentioned MIMO models. They concluded that adaptive control was superior in performance but at the cost of requiring a detailed, structurally correct model of the process through extensive simulation studies. But, intelligent control was less intensive and could achieve 10ms sampling rate with quick implementation. Schils et al [64] used a switching arrangement between the mean BP and the EEG for anaesthetic depth pointing to the need for intelligence in measurement.

An important example of intelligent controllers is the knowledge-based feedback Fuzzy-logic controller known as Self-Organizing Fuzzy-Logic Controller (SOFLC) [65]. In order to understand the Fuzzy-logic control strategy, the following example is given [9]:

It is possible to control the speed of a motor-car so that it is constant with the following set of rules:

IF (speed is low) THEN (accelerate slightly),

IF (speed is high) THEN (decelerate),

IF (speed is very high) THEN (brake) and

IF (speed is low and the road is uphill) THEN (accelerate sharply). The low, high and very high values have to be defined.

The Fuzzy-logic controller is self-organized and knowledge-based as the variables have Fuzzy (more – or – less) values. A Fuzzy knowledge-base is similar to the knowledge-base in the motor-car example containing rules of the type IF (error in target BP is slightly negative) THEN (fresh gas concentration should be small). So, they make use of the simple rule "if x then y" for passing the knowledge and experience of the anaesthetist. In this way a Fuzzy-logic control of inspired isoflurane concentration was achieved during minimal flow anaesthesia with reliable and reduced anaesthetic gas delivery and costs [9]. For patient safety, the Fuzzy control mode can be switched to human control in an emergency situation.

The SOFLC scheme has been used for administration of anaesthetics based on measurement of a sole indicator as systolic BP, HR or respiratory rate (RR)[66]. A step further is based on an expert system adapted for on-line advice. The Real-time Expert System for Advice and Control (RESAC) has been constructed for feedback control applications. It accepted both clinical signs entered by the anaesthetist and online measurements as systolic BP, HR and RR. From data logged during the clinical trials, it has been possible to validate the advice accuracy. Assessment of a successful operating procedure was via subjective appraisal by the anaesthetist and the surgeon, and by an objective indicator based on the expected time for the patient to wake up from anaesthesia.

Satisfactory performance of RESAC was indicated by both these indices [67].

Intelligent control strategies can utilize the extensive computational capabilities available to day to "reason" about the current state and to "detect" changes. They can use quantitative and qualitative models of system behaviour which are augmented by extensive sensor inputs.

Computer technology has recently borrowed numerous terms from biology and psychology as "adaptation", "neural" and "learning". Such terms could help in the advance of computer science with the use of a most recent term "intelligence". While adaptative controllers are well-structured learning control systems, intelligent controllers have the ability of "decision-making" and will gradually take larger shares in automatic control of anaesthesia and anaesthetic crisis. It should be understood, however, that intelligence is a function of the state of knowledge of the moment, to the extent that an intelligent control of today would be a conventional control of tomorrow.

It is evident that adaptive and intelligent controls are used as on-line feedback for drug administration via computer-controllers. However, intelligent alarm-handling in anaesthesia is important [66]. Matsiras [68] has produced a declarative-style intelligent alarm handler called PONI. In his work, he demonstrated a considerable reduction in false alarms which could be achieved via intelligent signal processing. This is very important, bearing in mind the enormous plethora of alarms triggered in the operating theatre conditions.

Thus, an encouraging progress has been made in adaptive and intelligent control of anaesthesia, but many questions remain as to their routine feasibility. The question of their acceptability by the clinical staff and the evaluation of the resulting on-line procedures as being beneficial to the patient must be constantly addressed. It is clear that consumed drugs are reduced in amount. This is both cost-effective and providing good operative conditions added to quick patient recovery.

5.6. Applications of controllers:

In addition to the perioperative application of advanced control systems in anaesthesia for controlling unconsciousness, muscle relaxation and PCA, these systems have the potential to be applied in other areas of medicine for which the feedback or feed-forward concepts are valid. Examples are, control of diabetes mellitus; administration of drugs for bronchial asthma as theophylline; administration of vasoactive drugs for arterial hypertension; administration of anticoagulants and delivery of antibiotics, antiarrhythmic and chemotherapeutic agents. The first three of these examples will be detailed as models for application areas.

5.6.1. Controlling insulin therapy:

Diabetes mellitus is a major chronic disease which affects approximately one hundred million people worldwide [69]. It is a lifelong condition; once diagnosed it cannot be cured and if not appropriately controlled, may lead to a variety of vascular,

neurological or metabolic complications. Good clinical management, can result in effective control of the patient's blood glucose level, may help to avoid (or at least to delay) such complications and requires a high level of clinical expertise. Since many of the treatment issues are amenable to analysis in control system terms, a greater understanding of the underlying control mechanisms offers the prospect of designing control algorithms and knowledge-based decision support systems which can lead to the wider availability of such high quality treatment.

In normal health the glucose/insulin interaction is a classical example of control exerted by an effective feedback loop. Elevation of blood glucose level (the controlled variable) results in the production of the hormone insulin by the pancreas (the controller). This insulin by means of its various effects upon glucose production and utilization, brings about a reduction of blood glucose from its elevated level.

Diabetes, in its form requiring insulin treatment, results from partial or complete failure of the pancreas to produce insulin in response to elevated blood glucose levels. (fig. 97) In the diabetic state, that internal control loop (the solid line) needs to be replaced by the external control loop (the dashed line). It should be noted that while the classical controller will usually be thought of as the doctor, in the case of chronic diseases such as diabetes, it is frequently the patient him/herself who makes the decision concerning the adjustment of insulin therapy, particularly on a day-to-day basis [55].

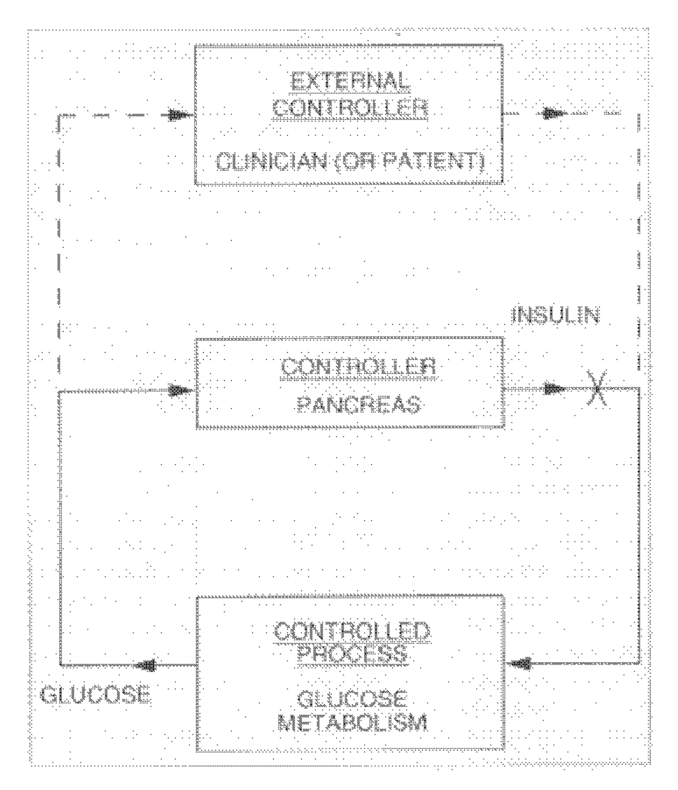


Figure 97: The scheme of glucose control in diabetic patients. The solid line (without the X) shows what happens in the normal situation. When the X (impairment of the control loop) stops the normal situation, the external controller is used (the dashed line).

In practice, the full picture is more complex and the diabetic patient needs to be regarded as a multi-input/multi-output (MIMO) physiological model which contains several controllable and measurable variables as well as other factors which are not directly observable and hence, as such, are beyond the clinician's control. The patient's diet (the carbohydrate content of which will directly elevate blood glucose level) and the dosage of insulin administered

can be considered to be control variables which need to be adjusted in order to maintain a balance between energy supply and expenditure with blood glucose being regulated at levels set by the clinician [70].

The nature of the problems faced in managing diabetes are such that a wide range of control system approaches has been attempted. Examining the literature over the past two decades, computer based approaches include knowledge-based systems to advise on patient management in outpatient clinics [70-72], as computer algorithms for insulin dosage adjustment [73-75] and diet planning [76]. Other approaches have employed techniques of optimal and adaptive control [77-79], assuming that the patient is being treated with a glucose-controlled infusion device such as an "artificial pancreas." Mathematical models have been used by a number of authors as a means of simulating or predicting blood glucose levels in the diabetic patient [80-84]. More recently, a range of examples using qualitative reasoning has been explored [85,86] as well as attempts to combine such qualitative approaches with quantitative simulation models [87]. This full spectrum of approaches is also to be found in the proceedings of a number of conferences [88-91].

Control system models:

A basic model of the clinical process can be defined in terms of the classical feedback loop. The clinician acting as the control unit compares measured and desired health profile and makes decisions resulting in instructions being given to medical or nursing staff (acting as effector or actuating unit). He then performs tests or

administers therapy directed towards bringing about a more desirable state of patient health (the controlled process). The actual health profile is then measured by means of the information system in the feedback loop, which in this context would include clinical consultations and examinations and laboratory data processing. However, feedback does not provide a complete model of clinical action and must be complemented by a feedforward action. This involves taking action in order to produce a desired state or to prevent an undesired state predicted as a possible consequence of disease progression or any anticipated disturbance in the future. The scheme of this anticipatory feedforward control action is based on a model describing the effect of disturbances and control actions on the system's output to be regulated [55]. Clinician control can thus be considered one of a feedforward action embedded within an overall feedback loop. This concept can be applied to many of the control situations that physicians are confronted with when treating diabetic patients.

Control schemes aimed at normalizing the patient's blood glucose are either closed-loop systems which determine the insulin infusion rate in accordance with the monitored blood glucose level; or open-loop systems which may involve pre-programmed short-term insulin delivery algorithms independent of a glucose sensor (feed-forward control), or rely on blood glucose observations collected over periods of home monitoring (intermittent feedback control). Open-loop control decisions may be related to single injections, daily treatment plans or long-term management protocols.

Control actions designed to have effect over different time scales require different quantities and qualities of data. There is also the need for different knowledge representation and decision-making schemes suitable to interpret these data and suggest treatment alternatives whenever needed. In data-rich situations which typically characterize closed-loop control, we find the extensive use of highly sophisticated adaptive control techniques. In contrast, methods at the data-poor end of the spectrum are mostly based on Fuzzy concepts (high blood glucose, excessive insulin action, etc.) and qualitative reasoning to draw appropriate therapeutic conclusions.

Closed-loop systems:

The development of the so-called artificial beta-cells (of the pancreas) constituted the first human imitation of the internal secretion of a gland (the pancreas). A closed-loop control system monitored the blood glucose level of the patient continuously and administered appropriate amounts of insulin calculated by control algorithms. A commercial version of an artificial pancreas has been also produced [92]. In the "model-independent" artificial pancreas, the feedback control algorithms for insulin delivery included linear or nonlinear PD controllers using the measured glucose level and its changing rate. The motivation for these schemes was that the controller should simulate the physiological behaviour of insulin secretion induced by glucose as in healthy subjects. However, in such systems, extensive preliminary tests were required to choose adequate controller parameters for a particular patient, since there

were individual differences and variations with time in the blood glucose regulatory mechanism.

More recent versions of "model-based" algorithms have been developed which determine the insulin infusion rate based on a model of the blood glucose regulatory dynamics in the patient rather than a model of insulin secretion [93]. The adaptive scheme is incorporated into the controller to identify the model coefficients in real-time so as to automatically adjust the controller parameters in accordance with important changes in the patient's glucoregulatory state.

While with this type of control system, normal blood glucose levels were quickly attained and maintained in response to a wide variety of challenges, including calorific intake, stress and physical exercise, unfortunately, none of these closed-loop systems has been used for more than 1 to 3 days [55]. Several factors, such as their size, the volume of blood needed, and the unreliability of both glucose sensors and continuous blood access devices impose practical limitations for their general clinical use. These limitations mean that currently open-loop systems represent the only practical way of managing diabetic patients routinely.

Recent research has been directed to the use of minimally invasive and non-invasive methods to measure blood sugar levels. Good glycaemic control has been demonstrated with a closed loop system using a subcutaneously implanted electroenzymatic glucose sensor [94]. An example is the continuous glucose monitoring system (CGMS) which is the only commercially available minimally

invasive blood glucose sensor approved by the Food and Drug Administration at USA (fig. 98).

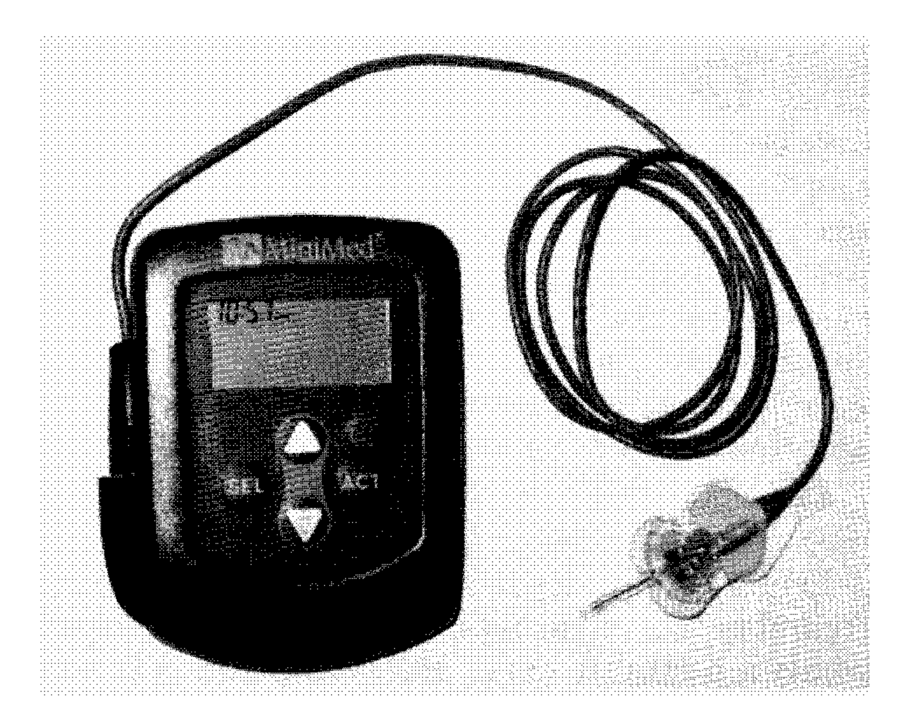


Figure 98: Continuous glucose monitoring system (CGMS) with glucose sensor attached

Chee et al [95] have recently described a closed loop system for the control of blood glucose levels in critically ill patients (fig. 99). It is composed of three components: a sensor, a controller and an infusion pump.

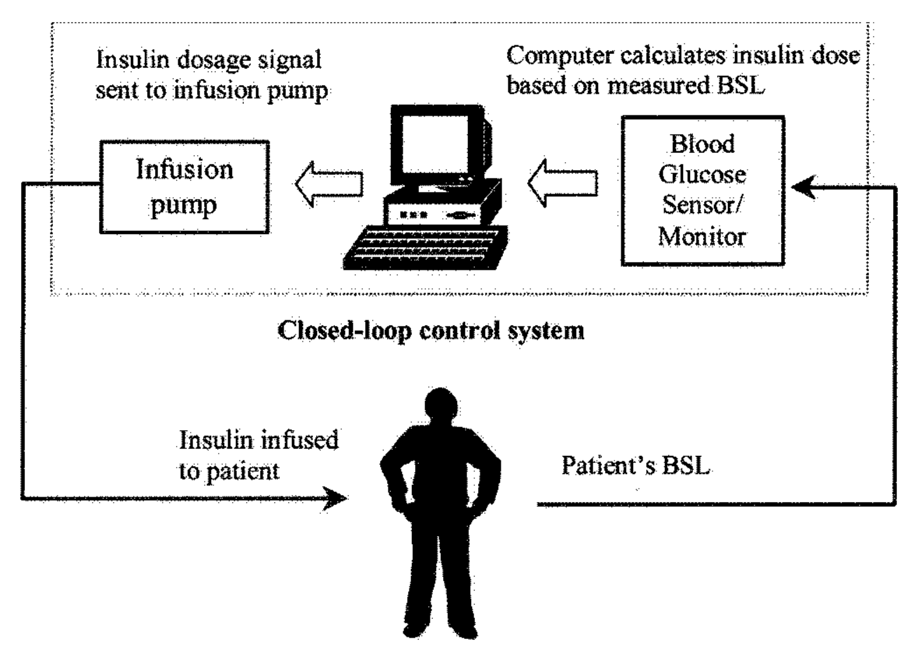


Figure 99: A closed-loop system for controlling blood sugar level in patients with diabetes mallitus

The glucose sensor is placed subcutaneously on the patients' anterior abdominal wall or the outer aspect of the upper arm, as convenient. The monitor is connected to the sensor. It is designed to be left for up to three days by the ambulant patient. CGMS takes a glucose measurement every ten seconds, and stores and reports an average of these values every five minutes. The glucose readings are downloaded onto a personal computer. The controller is responsible for coordinating the download of the readings from the sensor, the calculation of insulin dose, the operation of the infusion pump, and the logging of all readings and associated events as alarms. An inherent pre-programmed sensor calibration method is used to

estimate blood glucose level for patient safety. Again, sensor readings which are 2 mmol/L lower than glucometer readings added to the patient safety.

Chee et al [95] described the use of this closed loop system to control the blood sugar level in nine critically-ill patients. The system provided acceptable glycaemic control, comparable to manual blood sugar control. However, they found that the main drawback of the system was the inaccuracy of the subcutaneous sensors, requiring frequent recalibrations when used in the real-time setting. They advised further development of the system to be suitable for routine clinical use.

Open-loop systems:

Patients with insulin-dependent diabetes striving to optimize their treatment must monitor blood glucose levels frequently. Several electronic blood glucose_ recording devices are available [96]. These contain computer systems which are capable of receiving, storing, and processing patient-entered data with respect to self-measured glucose concentrations, estimated dietary intake and anticipated physical exercise. Some of them provide therapeutic advice based on past as well as current blood (or urine) glucose and insulin data [97].

The daily insulin dosage that the patient requires to maintain a reasonable degree of control, when keeping food intake and energy expenditure relatively constant, is called the basic insulin dose. Alterations in this regime, for whatever reason, are called

adjustments. In contrast to adjustments in the basic daily insulin dosage made as part of a feedback process, anticipatory insulin supplements associated with feedforward actions are temporary changes in the currently administered regime. Such actions are aimed to counteract the anticipated effect of future disturbances such as an unusually large meal or an increase in activity before they could produce unwanted elevation (hyperglycaemia) or depression (hypoglycaemia) of blood glucose level.

Short-term feed-forward control:

Traditional diabetes management, with strict limitations on meals and insulin injections, imposes a heavy burden on the patient's life style. The possible use of feed-forward control action, however, permits patients to deviate even substantially from their usual life patterns. When this occurs, the patient must estimate the change from the usual carbohydrate intake (in grams) or in the intensity of anticipated physical activity, and modify the timing and/or dose of the appropriate insulin dose accordingly. Parallel attempts to allow greater flexibility in the lifestyle of diabetic patients, while also improving the quality of their blood glucose control, have led in the early 1980's to the development of insulin infusion pumps [55]. In contrast to the "non-physiological" bolus injections that constitute traditional insulin treatment, such devices allow insulin to be infused continuously at rates, and for periods, set by the clinician or by the patient.

Feed-back control on a daily basis:

One of the most common control tasks in diabetes management involves planning insulin dosage regimens on a day-to-day basis. Different algorithmic, knowledge-based, and model-based approaches have been used to assist in solving this control problem. While algorithmic methods use branching logic to identify the patient's condition and propose the corresponding prestored therapeutic advice, rule-based approaches generally use "features" in the patient's blood glucose profiles as guides for making adjustment in the basic insulin dosage. The corresponding control action is activated when a particular feature, or a combination of features, is present or absent on two or more consecutive days in the patient's blood glucose profile [39].

5.6.2. Controlling theophylline therapy:

Theophylline is a potent bronchodilator used in the treatment of acute and chronic asthma [98]. The toxic and therapeutic effects of theophylline are related to the concentration of the drug in a patient's blood serum. Serum concentrations between 10 and 20 mcg/ml produce a therapeutic effect. The drug is likely to be ineffective at lower concentrations. Symptoms of toxicity may occur at higher concentrations, and severe toxicity may occur at concentrations above 30 mcg/ml. Pharmacokinetic models, which describe the time course of drug uptake, distribution, and elimination, are frequently used to predict the serum concentration resulting from a dose or infusion. Such models are useful for

determining dosing strategies or infusion regimens that will achieve and maintain a therapeutic serum concentration.

Theophylline is administered by intravenous infusion to provide rapid relief of acute asthmatic symptoms. The infusion regimen usually consists of a loading dose followed by a continuous infusion. The loading dose and rate of continuous infusion are calculated based on the average values of the pharmacokinetic parameters in the patient population. The loading dose is calculated to achieve the desired concentration for the volume of distribution. The clearance is used to determine the rate of continuous infusion required to maintain a desired concentration in the steady state. The ranges of the parameters may be considered in limiting the loading dose or infusion rate to decrease the likelihood of achieving toxic concentrations in patients with extreme values of pharmacokinetic parameters.

Since there is a wide variability in the pharmacokinetic parameters between patients, the dosage should be adjusted for an individual patient based on measurements of the serum concentration [98]. Thirty minutes to one hour after the loading dose, the serum concentration is measured to determine if additional loading doses are necessary, or if the measured concentration exceeds the desired value. After the continuous infusion is begun, the serum concentration will rise or fall if the patient's clearance is significantly different from the value used to compute the continuous infusion rate. A second serum concentration measurement obtained six to eight hours after starting the infusion may be used as the basis for infusion rate adjustment to compensate

for the difference between the patient's clearance and the assumed value for which the continuous infusion rate is designed. A third measurement may be obtained at twenty four hours to determine if an additional infusion rate adjustment is required. Additional measurements may be obtained every twenty four hours to allow the infusion rate to be adjusted to compensate for any clearance changes that may occur.

Adaptive control:

Model-based control is the basis of the adaptive control system employed in the simulation of theophylline therapy [99]. The infusion regimen is computed to achieve and maintain a target concentration in a pharmacokinetic model. The model parameters are initially set to the best estimates available given the prior information about the patient. When a measurement of the patient response is available, the parameters of the individual patient, and the model parameters are adapted to the new parameter estimates for the patient. The infusion rate is then automatically adjusted as required to move the concentration to the target level. In an implementation of the adaptive control system, the infusion regimen would be automatically delivered by means of a computer-controlled infusion pump or syringe pump, depending on the clinical setting.

With open-loop control, there is a significant number of patients for whom theophylline concentration is outside the therapeutic range of 10 to 20 mcg/ml. The wide variability in achieved concentrations demonstrates the need for infusion rate

adjustment based on the concentrations measured in an individual patient. With adaptive control based on samples obtained at 1, 8, and 24 hours, the variability in achieved concentrations is greatly reduced.

Optimal sampling theory suggests that for the accurate estimation of a parameter, a sample should be obtained at a time when the influence of the parameter on the measured variable is at a maximum [100]. Since the influence of the volume of distribution on the concentration is near its maximum at the one hour sampling time, an estimate of the patient's volume of distribution based on the one-hour sample would be expected to be accurate. The most accurate clearance estimate would be obtained from a sample drawn after the pharmacokinetic system has reached steady state, when the concentration depends solely on the clearance [101]. The 8 hour sample allows the infusion regimen to be adjusted for improved control, even though the sampling time is not optimal for estimation of the clearance. The 24 hour sample provides a more accurate clearance estimate that allows for precise control of the concentration in the steady state.

If the target concentration is 15mcg/ml in the early phases of either open-loop or adaptive control, a potentially toxic concentration may result in patients having a volume of distribution that is significantly less than the average value for which the early infusion regimen is designed [99]. With the second adaptive control strategy, the estimate of the volume of distribution based on the first sample allows the target concentration to be increased safely from 10 to 15 mcg/ml. The maximum concentration achieved during the

simulation does not exceed 20 mcg/ml in any patient. After 10 hours, the concentration does not fall below 10mcg/ml in any patient.

Previous simulation studies of adaptive control of theophylline therapy utilized the simple strategy of adjusting the maintenance infusion rate with a goal of achieving the target concentration in the steady state [101].

5.6.3. Controlling potassium therapy:

Abnormalities of plasma potassium (K+) concentration are a common problem in patients undergoing major surgery and in those requiring intensive care. Treatment is empirical, depending on frequent blood sampling to follow the response to therapy. Even with the rapid results available from potassium ion-selective electrodes, correction of abnormalities and maintenance of a stable plasma K+ may be difficult.

Automatic feedback control may provide a system for rapid, safe correction of plasma K+. Heining et al [102] described such a system, and its use in experimental animals.

Six dogs were anaesthetized with halothane and their lungs ventilated to a constant $PaCO_2$ of approximately 4kPa. Sodium bicarbonate was given if the base excess of arterial blood deviated beyond -8, samples for blood-gas analysis being taken every hour.

Plasma potassium was monitored continuously by means of a selective electrode inserted into the femoral artery. The electrode output was fed to an amplifier and subsequently passed through a

filter and the electrode was calibrated. Usually, the animal was heparinized to prevent clot formation on the electrode tip. (fig. 100)

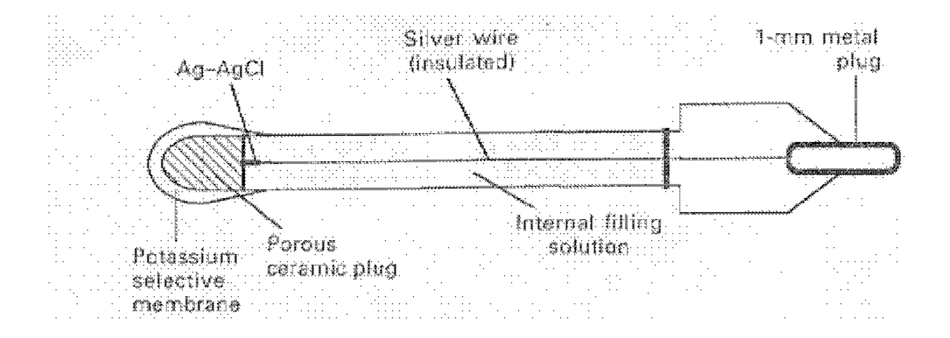


Figure 100: The potassium electrode

The control algorithm was written in BASIC on an IBM personal computer, and used a conventional PID system with separate control equations for the potassium chloride and the glucose-insulin infusions. The control system was arranged so that one infusion declined to zero when the other infusion started, so that both infusions were not running simultaneously. The output from the control program drove two specially adapted infusion pumps which were fed into a peripheral vein. One of these contained a concentrated solution of potassium chloride (50mmol/L or 200mmol/L) and the other contained 50% glucose with insulin 200μ/litre. The maximum rate of infusion of potassium chloride was 2.5 mol/kg / h, and the maximum rate of infusion of the glucose-insulin solution was insulin 5 u/kg/ h. Plasma K+ was measured every 10 seconds and infusion rates were adjusted every 1 min. The arrangement of the feedback loop is summarized in figure (101).

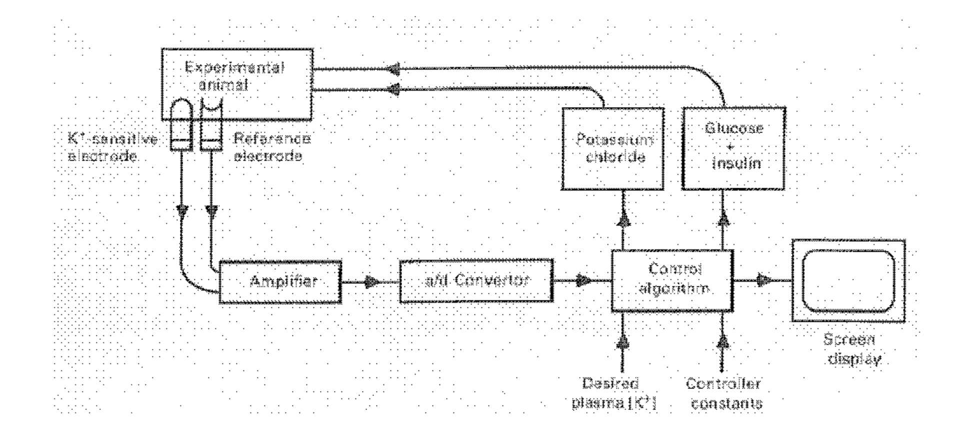


Figure 101: The feedback loop for automatic control of plasma concentration of potassium

The program also produced a screen display. This was updated every min to display the changes over the previous 40 min in plasma K+ (mmol/L), total i.v. infusion rate (L/h), potassium infusion rate (mmol/kg/h), insulin infusion rate (u/kg/h), urine flow (ml/h) and potassium excretion rate (mmol/kg /h). The last two were obtained from an electronic urine-meter and a flow-through potassium ion-selective electrode in the urine outflow. The screen display also gave the current status of the infusion pumps and their rates (ml/h), in addition to the current values of all the graphic displays.

The results showed that such a system was possible to construct; monitoring of plasma K+ was reliable, relevant data were stored, and stable concentrations of plasma K+ were achieved in healthy dogs. The conservative system increased plasma K+ to the

higher set-point in about 1-1.5h, with a gradually reducing rate of infusion of potassium chloride.

The response rate of the glucose-insulin system for reducing plasma K+ was slower, as the response depended on a physiological action and not on a simple chemical change.

So, the system was described for automatic feedback control of plasma potassium concentration in experimental animals. Plasma potassium was monitored continuously and the signal compared with the desired plasma potassium concentration. The resulting error signal controlled the infusion rates of a concentrated potassium chloride solution (50 or 200 mmol/L) and a solution of 50% glucose with insulin 200u/L. Plasma potassium was increased or decreased to the desired concentration at various rates, dictated by the controller constants. This system introduces an acceptable approach for its application for potassium therapy in clinical settings.

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6 Bioengineering versus Ergonomic Management

6.1 Bioengineering management

6.2. Ergonomic management

References

6. Bioengineering versus Ergonomic Management

In medical practice, bioengineering is the science which deals with the interface between the equipment and the patient. On the other hand, ergonomics is the science which deals with the interface between the equipment and the medical practitioner denoting that it is the scientific study of the medical practitioner at the work-place.

6.1. Bioengineering management:

Both anaesthesia and intensive care are heavily dependent on the hospitals' engineering systems. It is almost an article of faith that the supply of oxygen, suction, nitrous oxide and medical breathing air should be permanently maintained. The same is usually expected for the electrical supply. However, each of these may fail and as a result morbidities and mortalities may be encountered.

Unfortunately, all the gases we use are similar, being colourless, odourless and supplied at similar pressures. There is no simple observation which will immediately distinguish one from another at a wall-outlet. However, failure to receive sufficient oxygen may be fatal, and assurance of oxygen supply is essential. This implies a duty to monitor oxygen supply. This is not only an engineering responsibility but is also a responsibility of each anaesthetist or intensivist. The clinical responsibility is to know how the gas supply system functions, to understand the significance of its warning alarms, and to ensure that each patient receives the appropriate gas supply correctly. Correct gas supply necessitates

checking the equipment before it is used and taking steps to monitor the supply as it is given to the patient.

Gas supplies are available from two sources; pipelines and cylinders. Pipelines should meet the standards of medical gas systems. Medical gas pipelines have been hazardous to patients from one of two causes; either they have delivered the wrong gas, or they have delivered no gas at all. Delivery of the wrong gas, which has occurred in almost every country, is usually due to misconnection during installation, so that a gas other than oxygen is present in an oxygen pipeline [1]. Misfilling of a liquid oxygen vacuum insulated evaporator with nitrogen has been reported [2], but usually there is a policy of dedicated supply tankers with non-interchangeable couplings which physically prevents such misfillings. Similarly, with cylinders supplying pipelines, there are physical barriers to misconnection [3]. Nitrous-oxide has a specific male instead of a female thread on the cylinder, so misconnection with air or oxygen cannot occur. However, it is possible to connect industrial nitrogen which is commonly used to power orthopaedic tools, onto the oxygen coupling and this is the main reason that only medical air should be used to power orthopaedic tools.

The possibility of failure of oxygen supply must always be anticipated. To avoid harm to the patients, it is important that the anaesthetist or the intensivist receives the earliest possible warning of impending failure (table 2).

This graded warning cannot be replaced by oxygen monitoring using an oxygen analyzer in the breathing circuit. The oxygen monitor in the breathing circuit is virtually a total failure

warning and as such reduces the time available to manage the problem before patients are harmed. It also does not warn areas which may have patients dependent on oxygen. So, the two warning systems (the oxygen supply impending failure alarm and the oxygen monitor total failure alarm in the breathing circuit) should be complementary to each other, and should not be viewed as alternatives.

Table (2): Recommended alarm systems for oxygen supply

Situation	**Colour indicator**			**Audible status**
	Green	Amber	Red	
System being supplied from a vacuum insulated evaporator, compressed gas cylinders or air compressor (Gas supply normal)	ON	OFF	OFF	OFF
System being supplied from a secondary supply (On secondary supply)	ON	ON Flashing, only changed to OFF with restoration to normal	OFF	ON With mute switch
System pressure has fallen below 320 kPa	OFF	OFF	ON Flashing	ON With mute switch

Anaesthetic machines are sometimes used in locations beyond the supply of piped gases and require cylinders for the supply of gases during anaesthesia. Cylinders may also be attached

to the anaesthetic machine as a backup in case of pipeline failure. In such cases, an oxygen pressure failure device as "Howison" or "Bosun" must be installed. Although an oxygen monitor in the breathing circuit would act as an alarm when an oxygen cylinder becomes empty, if the monitor is not attached or is not switched on, the patient is at great risk. Again, these two monitors (the oxygen pressure failure alarm and the oxygen monitor alarm in the breathing circuit) are complementary and not alternatives. All low pressure alarms are self-activating and are less susceptible to operation error. Safety guidelines require an oxygen pressure failure warning device to be present on each anaesthetic machine [4].

The current technology is well established to provide an accurate oxygen analyzer in the breathing circuit. Although some analyzers have been reported to be affected by agents as water vapour, volatile anaesthetics or nitrous oxide [5], most available analyzers today are reasonably resistant to these effects. It is important to note that the use of a pulse oximeter does not nullify the use of an oxygen analyzer because each device provides different information. The oxygen analyzer monitors the oxygen concentration in the patient's inspired gas, and is thus a machine and breathing circuit monitor, whereas the pulse oximeter monitors the patient's haemoglobin saturation and is thus a monitor of tissue oxygen delivery and will only provide a very late warning that something is wrong if a hypoxic gas mixture is supplied. For both anaesthetic and intensive care use, oxygen analyzers must have a low alarm which should be both visible and audible. Better still, these analyzers should have adjustable higher and lower alarm

limits. A two-point calibration check using air and oxygen and a check of the low level alarm should be carried out before use.

Loss of electrical supply in operating rooms and intensive care areas may occur and may be general or local. General loss of electrical supply is usually obvious because both the power and lighting are affected. The restoration of supply is usually prompt if an automatic emergency generator system has been installed. However, it is important that both anaesthetists and intensivists know if their areas have emergency power, when it is tested and which sockets within the patient areas are supplied by the emergency generator system.

In the past, flammable anaesthetic agents were frequently used and fires or explosion hazards were of paramount importance to anaesthetists. However, fires and explosions still take place and are being still reported causing serious injuries to patients or operating room personnel. It is important to familiarize the anaesthetists with such risks. The hospital engineering system and the anaesthetists should provide strategies on how to decrease these risks. Anaesthetists should be trained to take care of patients, should a fire occurs. Of specific importance is to consider the various types of medical lasers and their implications for the anaesthetists.

If a fire develops, it is important to know how to extinguish it as rapidly as possible. Breaking the fire triad is extremely important. Removing the oxidizer by disconnecting the oxygen or the circuit from the patient will usually extinguish the fire. Burning

drapes should be removed quickly to the ground and extinguished. All personnel should be familiar with fire extinguishers (fig. 102).

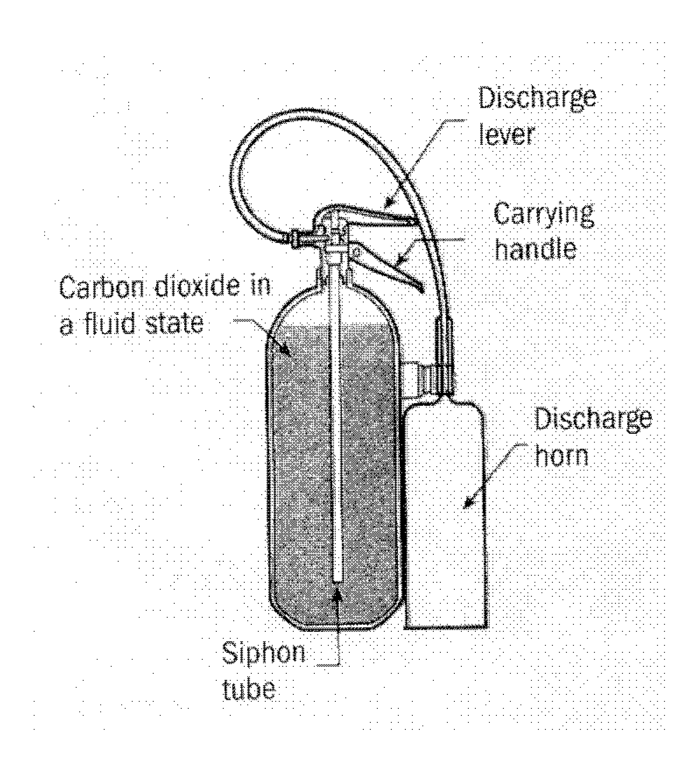


Figure 102: Fire extinguisher

It should be clear that prevention is better than trying to deal with an established fire and to have a clear plan for dealing with fires and explosions including a sound alarming system and a way for rapid evacuation of people (fig. 103).

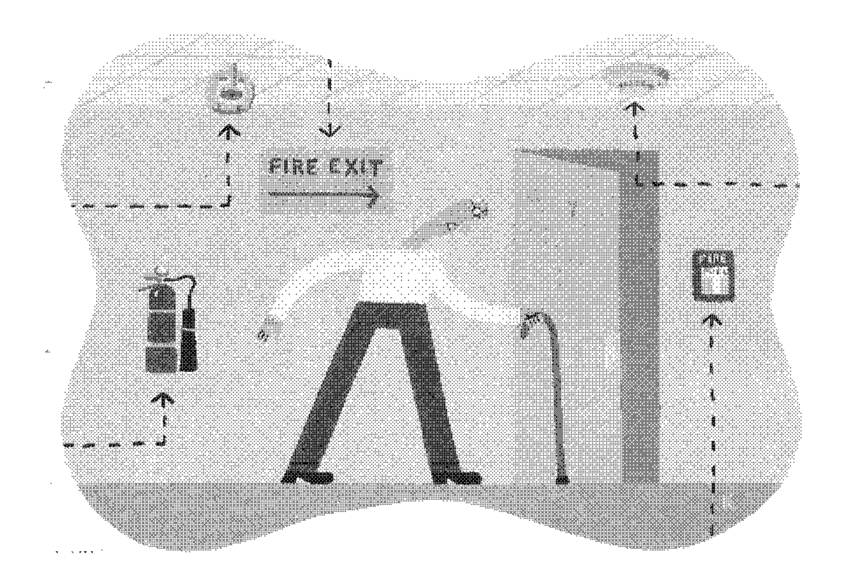


Figure 103: Fire exit

Before commencing any general or local anaesthetic, there should be a thorough check of all the equipment which may be needed. This has been likened to the check performed by a pilot before taking off in an aircraft. This must be done in a similar systematic fashion so that the possibility of missing or faulty equipment is reduced to a minimum. The check should cover the anaesthetic machine analogous to the pilot checking the exterior of the aircraft by walking around it and testing various parts.

Allnut [6] has given an account of the similarities between pilots and anaesthetists and their task requirements: "... both pilots and anaesthetists are carefully selected, highly trained professionals who are usually determined to maintain high standards, both

externally and internally imposed, whilst performing difficult tasks in life-threatening environments. Both use high technology equipment and function as key members of a team of specialists, although not always with colleagues of their choosing, and are sometimes forced to operate at a time and under conditions which are far from ideal. Finally, they both exercise high level cognitive skills in a most complex domain about which much is known, but where much remains to be discovered". Another similarity is that both are faced from time to time with rapidly evolving crises of a complexity which requires cognitive tasking that is beyond the information-processing capacity of the human brain. [7] Also, they both operate systems in which one false move may have an immediate and catastrophic consequence, where the cause-effect relationship is obvious. The problem may be further compounded by valuable cognitive processing capacity being directed towards worrying about the sequelae of an impending disaster.

It is well recognised by aviation psychologists that the best strategy in such a situation is to default to a well-learned and frequently practised routine which has been designed to render the system safe while diagnostic and corrective measures can be implemented [8]. Much effort is expended in refining and simplifying these "immediate response" or "phase I" algorithms, as, even with the mandatory 3-monthly testing required for airline pilots, such skills degrade rapidly if they are complex. The new Boeing 747 aircraft have only 7 "phase I" sequences, whereas the original "classic" B747 had 36. It is curious that the only such algorithm widely used in clinical medicine is the "cardiopulmonary

resuscitation" routine, which is well down the disaster path. It was decided in 1988 [9] to try to develop an approach to crisis management in anaesthesia; based on or similar to phase I aviation algorithm.

A two-day workshop was held in Ballarat in November, 1988, and was attended by 60 anaesthetists and representatives of the Australian Bureau of Air Safety Investigation (BASI). Six "familiar" anaesthetists were asked to prepare and present a crisis management algorithm for each (table 3); each was unaware that the other had the same task. These were presented at the meeting; the presentations precipitated intense debate, with the exchange of many strongly held views. An almost complete lack of consensus, and the fact that no widely accepted algorithms existed for common, dangerous situations, led the aviation psychologists at the meeting to embark on a program of healthy living, while the presentation of several aviation crisis videos resulted in the revision of the travel plans of several anaesthetists.

Table (3): Algorithms presented at the Ballarat Crisis Management Workshop

"I can't ventilate the patient"
"I can't get a blood pressure"
"I can't see he larynx"
"The blood is a bit blue down here"
"The pulse feels fast and irregular"
"The patient won't stop bleeding"

It was clear from this Australian Incident Monitoring Study (AIMS) [10] reports that certain incidents had prolonged courses or bad outcomes because of inadequate crisis management; this observation was supported by the demonstration that even experienced anaesthetists often performed badly in simulated crises. [11-13] At this stage, two schools of thought prevailed. One held that specific crisis-management algorithms should be developed based on "pattern recognition" of which type of crisis was evolving; in contrast, the authors felt that the risk of choosing a "wrong" algorithm was too great and that a "core algorithm" suitable for the initial response to any crisis should be developed in an objective a manner as possible in an attempt to "secure the system" before branching into "sub-algorithms".

A one-day workshop was held in Sydney in May 1991 at which it was decided to concentrate on algorithms for use in the operating theatre when an anaesthetic machine was in use; about 100 anaesthetists and representatives from ABASI attended. A "core" algorithm – "COVER ABCD, A SWIFT CHECK"; COVER for the general problem "something is wrong", was evaluated and presented while other participants presented updated algorithms for specific situations (Table 4).

Table (4): Algorithms presented at the Sydney Management Workshop

Algorithms
"Something is wrong"
"I can't ventilate the patient"
"I can't feel a pulse"
"The blood is blue "

COVER denotes: C1 for circulation, C2 for colour, O1 for oxygen, O2 for oxygen analyzer, V1 for ventilation, V2 for vaporizer; E1 for endotracheal tube, E2 for eliminating the anaesthetic machine with self-inflating bag with 100% oxygen, R1 for reviewing the monitors, R2 for reviewing the equipments. A,B,C and D stand for Airway, Breathing, Circulation and Drugs.

A second phase was entered into of reviewing the literature, keeping a watching brief on accumulating AIMS reports and discussing possible solutions to the problems listed above. The COVER algorithm was presented at a meeting in Monterey, California, in February 1991 on "Human Error in Anaesthesia" sponsored by the FDA (USA) and the Anesthesia Patient Safety Foundation (USA) and obtained the general approval of some experienced psychologists and human performance experts. [14]

So, it is clear that anaesthetists are called upon to manage complex life-threatening crises at a moment's notice. As there is evidence that this may require cognitive tasking beyond the information-processing capacity of the human brain, it was useful to try and develop a generic crisis management algorithm analogous to the "Phase I" immediate response routine used by airline pilots. [15]

For satisfying patient safety during anaesthesia, all the equipment required for airway management or suction and all anaesthetic and monitoring devices should be also checked. It should be noted that vaporizers have had to change recently because of the introduction of desflurane. The last time that vaporizers changed significantly was with the introduction of halothane five decades ago. It became apparent at that time that the available ways

of delivering ether were going to be inadequate and even dangerous for this new potent inhalational agent with relative rapid action and severe cardiovascular depression properties. Desflurane requires a special vaporizer because it boils at room temperature, although not at the temperature at which operating rooms are maintained [16]. On the whole, all vaporizers should be routinely checked and periodically calibrated during the course of their use.

If a ventilator is to be used, the tidal volume should be measured by a respirometer. A functioning disconnection alarm should be correctly sited in the expiratory limb of the breathing circuit.

Devices which need to warm-up and stabilize as some oxygen analyzers should be allowed to do so. If equipped with an alarm, a device should be turned on, adjusted to suitable settings and checked. The sensor of each monitor should be placed so as to yield maximum information, and the display placed so as to be visible. The operator should be aware with the specificity and sensitivity of each device and the possible pitfalls and their management.

Perhaps, the checkout process is time consuming. The solution may be to automate the process, a task of new computerized anaesthetic work-station that is currently being developed [16].

6.2. Ergonomic management:

In the operating theatre, individual components of monitoring devices and other pieces of equipment surround the anaesthetist randomly. S/he is positioned among an array of devices which cover up to 270 ° in the horizontal plane and up to 120 ° in the vertical plane [17]. Collected data are sometimes non-coordinated, and information from one device to another may not be transformed. Although each monitor is separately ideal, collection of different monitors may be ergonomically unsatisfactory. The operating theatre, as a work place, can be improved by providing adequate relationship between the anaesthetist and different pieces of equipment. This is because the scatter of the complex controls, alarms and displays have the potential to inhibit vigilance and to cause human errors. The integration of different monitored data and alarms into one compact display provides an ergonomic advantage for the comfort of the anaesthetist and the safety of the patient (fig.104). A brief glance to the compact display provides sufficient information without distraction. Displayed data can be checked digitally and a reset button can re-establish a normal range. The same can be applied to different alarms according to the judgment of the anaesthetist who can modify a variable or reset a normal range. A temporary mute of an audible alarm may be also an advantage.



Figure 104: The integration of different monitored data and alarms into one compact display provides an ergonomic advantage

Ergonomics are of major importance for processes which place demands on human cognitive abilities. It is very important that this applies to alarms. On intensive care wards and the operating theatres, several alarms may sound simultaneously. The intensivist or anaesthetist must first locate the source of the alarms, exclude artifacts ad deduce causative disturbances of the patient condition [18]. The greater the variety of the devices used in anaesthesia and intensive care, the more complicated their handling becomes. This increases the probability of operating errors due to the stress placed on the operator. From an ergonomic point of view, data displays and operating elements must be designed to be as simple as possible. The control panel would be extremely confusing if each function is allocated a separate operating element. Instead, different operating elements can be reduced by the multiple use of keys or menu structures [19].

Currently used monitoring devices are manufactured with regard to ergonomics which should be always considered during equipment purchasing by the hospital.

Specially in ergonomic settings as the operating theatre and the intensive care unit, the principal function of technology information is to augment operator expertise [20]. So, any analysis of technology inevitably becomes an analysis of the operator and vice versa. This may constitute adequate training and experience for the conduct of anaesthesia and intensive care management.

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7 Minimal Monitoring Standards

7.1. Machine monitoring

7.2. Patient monitoring

References

7. Minimal Monitoring Standards

Since the dawn of the practice of surgery under anaesthesia, morbidities and mortalities have been repeatedly recorded, and would have been reduced or even prevented by adequate monitoring. Added to proper history taking and clinical examination, patient safety can be achieved by skilled management under adequate monitoring of both the anaesthetic machine and the patient.

7.1. Machine monitoring

For machine monitoring important points should be considered. If a piped oxygen is to be used, there must be an oxygen supply failure alarm added to an oxygen analyzer and if cylinders are to be used there must be a suitable oxygen supply failure alarm fitted to the anaesthetic machine. If the patient is dependent on mechanical ventilation of the lungs, a reliable mechanism for detecting failure of ventilation is essential. Whether this is designed as a part of the ventilator or as a separate piece of apparatus capable of operating with any mechanical system of ventilation is not important, so long as the system is reliable. A useful analysis of the features and performance of these devices has been carried out by Myerson et al [1].

Machine monitoring at present also includes regular on-line analysis of volatile agent concentrations, either in the inspiratory or expiratory limbs of the breathing circuit, or both. This is of advantage – if available – for patient safety.

7.2. Patient monitoring

For patient monitoring, the most important monitoring "device" is the attendance of an experienced anaesthetist at all times. This is because monitoring devices are useful adjuncts, but alone they cannot replace his or her care and vigilance [2]. Mortalities and morbidities are routines reported to specific committees or to medical defence organisations in which, in retrospect, patients' lives and brains would have been saved by the attendance of anaesthetists close to the patients and by the use of monitoring devices. On some occasions, such devices were not present and on some others, they were available and the anaesthetist did not use them. No amount of rationalisation is likely to convince a court that the anaesthetist was not negligible if it could be proved that a relevant monitor was available, the anaesthetist knew that it was available and s/he did not use it, and if it had been used, the patient would probably have not come to any harm [3]. Every event of this nature, reaching the court or not, adds pressure on anaesthetists to accept minimal monitoring standards. If such standards are not set by anaesthetists, they would be determined by other persons unfamiliar with the speciality. So, minimal monitoring standards, for the machine and the patient, must be established by anaesthetic authorities in different locations according to available circumstances.

A paper entitled "standards of patient monitoring during anaesthesia at Harvard Medical School" [4], was editorialised in JAMA [5], and later taken up by the American Society of Anesthesiologists [6]. The World Federation of Societies of Anaesthesiologists has also adopted international standards for safe

anaesthesia [7]. The standards are flexible enough to allow improvement in anaesthetic practice in any country, no matter what the economic status may be.

Those standards demand the presence of anaesthetists during all general and regional anaesthetic settings. Blood pressure and heart rate measurements are to be recorded at least every five minutes, with some form of continuous clinical or machine monitoring of ventilation and circulation. Continuous palpation of the reservoir breathing bag and pulse is considered acceptable, as is continuous auscultation of breath and heart sounds. Oxygen analyzers and ventilator disconnection monitors, both with audible alarms, are to be used when anaesthetic machines and ventilators are respectively, in use. A means to measure the temperature must be readily available. Every patient is also required to have a continuously displayed ECG from induction of anaesthesia until being prepared to leave the anaesthetising location. At that time, the use of end-tidal carbon dioxide monitoring and pulse oximetry was not mandatory, but it was indicated that this might become so at some stage in the future. However, the impact of pulse oximeters and end-tidal carbon dioxide monitoring devices on the thinking of the anaesthesia community has been susbstantial and an increase in litigation has further changed the environment of anaesthetic practice [8].

The current concept for patient monitoring is that a patient needs simple monitoring if s/he belongs to ASA I class, the operation is simple, brief, minimally invasive and needs no muscle relaxation. For such a patient a satisfactory standard of care is the

attendance of a trained anaesthetist carefully observing the reservoir bag with fingers on the pulse or a stethoscope on the precordium, together with regular measurements of the arterial blood pressure by a manual sphygmomanometer. This is added to the use of a pulse oximeter for assessing oxygenation.

If we imagine that a monitor is usually suspended on a stand, and that the vertebral column of the attending physician or nurse is such a stand, then this stand carries so many "human monitors" as vision, audition and touch. These monitors are dedicated for patient care so long as they are near to the patient. So, an attending physician or nurse –with so many human monitors – near to the patient can do a good job for patient safety. On the other hand, a physician or nurse away from the patient deprives him/her from the key services of those "human monitors". This is because "human monitors" cannot only interpret the patient condition but can supervise other monitoring devices, whatever sophisticated, as well.

A patient of another category needs a more monitoring standard. This represents a longer operation with greater risk or an operation carried out at a suboptimal environment as in the radiology department. Greater risk implies the need to define criteria which separately or combined can guide the amount of escalated monitoring, including extremes of age or body weight, the presence or pre-existing disease comprising the patient condition, the need for controlled ventilation under muscle relaxants, the need for vaso-active drugs for induced hypotension or the expectation of blood loss and fluid shifts. The amount of monitoring devices should be tailored to the patient needs including an ECG, a

capnogram, an electronic thermometer, a monitor for measuring expired anaesthetic concentrations or a peripheral nerve stimulator. Each of these monitors and others has a certain indication and can provide information of specific value in a certain situation. Spirometry, invasive monitoring of cardiac filling pressures by central venous or pulmonary artery catheters and monitoring ABG's may be added if mandatory.

The proportion of anaesthesia related morbidity and mortality occurring in the early postoperative period remains fairly constant and is largely preventable. The recovery room must therefore be considered as important as the operating theatre or the ICU. The quality of the staff, the design of the area and the provided facilities should also reflect minimum monitoring standards of patient care.

The anaesthetist is responsible for the patient until the airway and breathing are adequate, consciousness has returned, protective reflexes have been regained and vital signs are stable.

The anaesthetist must accompany the patient to the recovery room, with the patient in the lateral position whenever possible. In the recovery room, the anaesthetist must ensure that the nurse responsible for the patient is fully informed of all the relevant facts about the patients medical history, the anaesthetic, the operation and the postoperative orders and should be warned about any potential problems. This handover should be formal and it is advisable that the anaesthetist should remain until the first set of observations has been made, as patient assessment is difficult during transit from the operating room to the recovery room. Whenever possible, information and instructions should be in writing. An anaesthetist

must always be available for rapid recall to deal with problems in the recovery room. In large busy recovery rooms, it may even be appropriate that the recovery room is supervised by specially designated medical staff. If a patient is to remain in the recovery room for a prolonged period, it is important that the surgeon also becomes involved in ongoing management and available for consultation if problems take place.

Patients usually remain in the recovery room for a minimum of thirty minutes and may remain longer depending on individual needs. An anaesthetist must authorise the patient discharge from the recovery room and must ensure that the patient meets specified discharge criteria which the nursing staff can apply. When the patient is discharged into the care of the ward nursing staff, the same quality of communication must be maintained to ensure continuity of care. Patients must be accompanied to the ward by staff members who are capable of dealing with problems that may occur during transit.

Day-care surgery is increasing and there is a trend towards patients being discharged home from a day-care ward or even directly from the recovery room. Recovery standards for day-care surgery are as important as those for inpatient procedures. A minimum period of one to two hours period of observation before discharge is required by most centers. Postoperative instructions must be understood by the patient and by a responsible accompanying adult person. Further written instructions must be provided and must include a contact at the hospital if needed. Instructions should be given for safe transport home, including

avoiding public transport, a limit on the distance travelled and the presence of a responsible person other than the driver. Patients or accompanying persons or both should be warned verbally and in writing about the dangers of driving, operating complex machinery or making important decisions, and the dangers of ingesting sedative drugs not prescribed by the physician.

Modern anaesthesia has reached the stage where even the most desperately-ill patients can be anaesthetized with considerable safety. However, the most heroic surgery, made possible by the most elegant anaesthesia and supported by the most sophisticated monitoring devices should be backed up by a safe, comprehensive recovery room service.

University, teaching, military and public health hospitals, where major surgeries are carried out, should provide non-invasive and invasive monitoring devices for satisfying adequate monitoring standards set by anaesthetic authorities. In conjunction with this requirement, regular programs for teaching the principles and the proper use of monitors should be initiated and maintained in every hospital. The concept including intensive teaching and quality assurance is mandatory for patient care in all hospitals.

Interest continues to grow in anaesthetic training by the use of simulators to improve performance. Simulators have a major role to play in training in aviation, fire fighting and control of nuclear power plants. In anaesthesia, they may be used to teach basic skills and to train anaesthetists in crisis management [9, 10]. So, the use of simulation to train anaesthetists in the intelligent use of monitors and equipment is an idea whose time has come.

A simulator consists of a manikin (in place of a patient), an anaesthetic machine with a ventilator and computer simulated monitors. Simulation presents clinical scenarios that test the ability of the trainee to deal with a specific emergency. Simulators are realistic and require appropriate responses to be performed by the trainee as manually ventilating the lungs. Anaesthetic simulators vary from low to high fidelity according to their complexity. High fidelity simulators gain higher acceptability by the user and are more able to reflect what happens in real life [11]. Individual performance for crisis management in a simulated setting can be tested and repeated for training until results are valid and reliable with an acceptable level of inter-observer variability. [12]

An example of anaesthetic simulators is the Anaesthetic Computer Controller Emergency Situation Simulator (ACCESS) which has been used over the last decade, being efficient in providing basic training for junior anaesthetists to improve their abilities for crisis management.

The use of high technology monitors and devices without sufficient training can induce harm to the patients. Russel [13] emphasised a law in the form of a statement: "any-time you develop something to solve a problem, you may solve the problem, but you may actually create new ones as well". Based on this, new ideas may produce new pieces of equipment which may produce new, or at least unexpected problems. This is actually avoided by proper training and education.

Another goal of education should be directed at other medical staff in the hospital. If those understand the nature of

anaesthetic risk, they will be supportive of practices that assure safety. In this domain, expressions applied to anaesthetic practice should be abnodoned in favour of term that convey meaningful reality. An example is the term "muscle relaxant" which suggests a soothing and quieting effect. It should be termed "paralysis agent" to appropriately describe its action and to convey the sense that this agent must be used with appropriate caution. [14]

It is clear, now, that the effects of technology on patient safety are controversal. While advanced technology produces safety by overcoming limitations of the physicians and decreasing their errors, applications of new technology are potent producers of new forms of failure. New technology tends to be used to accomplish new things rather than to simply do old things better or more safe [15].

Improvements of patient safety during anaesthesia and surgery grow out of the power and authority conferred by the specialities on the practitioners and the ability to use such power and authority to induce influence and control. Patient safety may not grow out from the technology itself, but rather from the developing specialities that understand what things are and what they mean.

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8 Monitoring and Risk Assessment

8.1. Risk asessment scoring systems

8.2. Monitoring programs for performance skills

References

8. Monitoring for Risk Assessment

Risk can be defined as the chance of adverse outcome and to the general population it implies a degree of danger. Risk assessment is dependent on an analysis of all the components within the system; both the patient and the healthcare providers. The two elements of the assessment process are identification and quantification of the risk. Identification depends on information and data collection, while quantification depends on a combination of clinical judgement and mathematical modelling. Risk analysis is not a static process as assessment needs to be revised in the light of new information, treatment strategies and techniques. While it assesses probability, the decision to proceed with a given course of action depends on how the patient is exposed to risk and how the healthcare provider can deal with it [1]. Healthcare providers sharing in patient risk include the anaesthetists, the surgeons and the nursing staff; adding to patient-related risk factors.

8.1. Risk assessment scoring systems

For patient risk assessment, the American Society of Anesthesiologists (ASA) classification is based on the preoperative history, clinical examination and interpretation of available investigations and can assign the patient to one of five categories (table 5). This can be considered a preliminary human monitor for the patient physical status.

Table 5: ASA classification of physical status	
ASA1	Normal healthy patient with no known organic, biochemical or psychiatric disease.
ASA2	Patient with mild to moderate systemic disease, e.g. mild asthmatic.
ASA3	Patient with severe systemic disease that limits normal activity. e.g. severe rheumatoid arthritis.
ASA4	Patient with severe systemic disease threatening his/her life, e.g. unstable angina.
ASA5	Patient who is moribund and unlikely to survive 24 hour.

The addition of the letter E, e.g. ASA4E, indicates those patients in whom emergency surgery is undertaken.

However, the ASA classification is subjective and fails to take into account the nature of the intended surgery. This led to the development of more objective risk assessment scoring systems focusing on organ dysfunction. Examples are the cardiac risk index (CRI) monitoring cardiac dysfunction [2], the pulmonary risk index (PRI) monitoring respiratory dysfunction [3], the cardiopulmonary risk index (CPRI) monitoring cardiopulmonary dysfunction [4], the predictive respiratory complication quotient (PRQ) monitoring postoperative risk of morbidity in patients for thoracic surgery undergoing lung resection [5] and monitoring hepatic reserves by Pugh et al [6] or Moemen et al [7, 8] scoring systems. Hematological, biochemical and radiological investigations added to different

classes of monitors [9] including the human monitors (class I) and/or monitoring devices of class II and class III can achieve an optimal risk assessment of the surgical patient. Machine monitoring should not be ignored.

8.2. Monitoring programs for perfromance skills

The role of **the anaesthetists** in the determination of patient adverse outcomes from surgery and anaesthesia has recently come into focus. Although there is a general tendency for surgical patients to be older and sicker, very large reductions in preoperative morbidity and mortality have been achieved over the last decades. Anaesthetists have long seased to simply put patients to sleep. However, the relative safety of anaesthesia is one of its most insidious hazards. There is a growing literature indicating that life-threatening complications can be observed not only in the intra-operative period, but also in the postoperative period. Therefore, it is very important to evaluate the anaesthetic component in the risk of surgical patients. Actually, anaesthetists are at the forefront of the development of systems aiming to monitor their performance [1]. Until simulators have been used to monitor performance and vigilance [10, 11], there was no reliable way of testing practical ability of a minimum standard, except for instituting systems for continuous medical education with monitoring learning and practical skills of anaesthetists through their career [1]. Anaesthetic simulators can be used to monitor the clinical skills of anaesthetists without comprising patient safety. Simulators use clinical scenarios, with appropriate levels of sensitivity and specificity, to

objectively assess the anaesthetist's response. Lessons learnt from the analysis of performance of these simulators will help to reduce the risk to the patient in real-life [1].

The Surgeons, undoubtedly, play an important role in the outcome from surgical operations. One means of monitoring the performance of the surgeon is the cumulative sum method (CUSUM) [12], that monitors sequential outcomes for a given surgical procedure to be plotted against adverse outcome over a period of time. The slope of the line allows assessment of the surgeon's performance and compares it to that of other surgeons. A refinement of the CUSUM method has been proposed which incorporates patient-related risk factors in the analysis of outcomes to be compared with predicted outcomes [13]. Although these methods are applicable to surgeons and specific surgeries, they cannot be used to track the performance of anaesthetists and theatre staff members.

Other **healthcare providers** including nurses share in the occurrence of adverse patient outcomes. This can be usually improved through a system in which organisations aim at continuously improving the quality of services and safeguarding high standards of care by creating an environment in which clinical excellence can flourish [14].

In general, the aim of any monitoring program of risk assessment should be to improve objectivity and to reduce subjectivity of the process. This can often be enhanced by the use of mathematical modelling [1].

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9 Summary

9. Summary

There is no doubt that the use of monitoring devices may yield information that adds to patient safety. However, if these devices are used inappropriately, they may confuse or mislead the physician. In spite of this, anaesthetists and intensivists take pride in understanding monitoring equipment and are keen to meet the challenge of the technological revolution for the safety of their patients.

Clinical monitoring starts with preoperative assessment of the surgical patient. This includes full history, clinical examination and necessary investigations. A summary of this preoperative consultation should be included in the patient record with a notation of the ASA status.

Before commencing any anaesthetic, there should be a thorough check of all the equipment which may be needed by the anaesthetist. Hospitals should have a policy governing the use of monitors, to minimize the risk of equipment related hazards and inappropriate failure in order to maximize equipment accuracy. So, patient safety is shared by both the physician and hospital responsibilities.

The anaesthetic record serves as a monitor for both the patient and the anaesthetist with a number of important functions. Basically, the anaesthetist is the only indispensable monitor for the patient, being responsible for his/her safety and well-being during the perioperative period.

A monitor consists of three components; a sensor, a system for data collection and organization and a system for interpretation. Any component may be "human" or may be some electrical or mechanical "device". There are four classes of monitors. In class I monitors, all components are "human". In class II monitors, the sensor is a "device". In class III monitors, the sensor and data collector are "devices". In class IV monitors; all components are "devices".

Currently, the most fundamental monitors are those of class I and II. Class III monitors still require human interpretation. Although class IV monitors are composed of component "devices", they should work under the control of the human anaesthetist.

Class I monitors represent "the human monitors" as all their components are human in nature in the form of human senses as vision, audition and touch. In conjunction with the human monitors of the anaesthetist, the patient can share as being a monitor for him/herself. Examples are diabetic surgical patients and those undergoing TURP or carotid endarterectomy under regional anaesthesia.

Class II monitors introduce mechanical or electrical sensors to extend the human senses of the anaesthetist for monitoring vital functions of his/her patient. Examples are the stethoscope and the manual sphygmomanometer. Both monitors are simple, mobile, cheap and easy to use. They can be considered close friends to the physician and the most minimum monitoring standards for patient care.

A class III monitor includes a "device" for sensing, a "device" for data collection and organisation, while interpretation is a "human" process. Examples are the non-invasive automated sphygmomanometer, the invasive cannula / transducer / amplifier / display arterial blood pressure monitoring system, the ECG, the pulse oximeter, the capnogram, the electronic thermometer, the nerve stimulator, the monitors for anaesthetic depth, the monitors for brain and spinal cord functions, the echocardiogram, thromboelastography, the central venous and pulmonary artery catheters, gastric tonometry and the monitors of respiratory and haemodynamic functions.

An automated sphygmomanometer displays systolic, diastolic and mean arterial blood pressure. It shows trends of repeated blood pressure measurements. Through setting alarm limits, it can alert the anaesthetist for serious blood pressure changes. It is convenient whenever it does not vary with a manual sphygmomanometer, as regular blood pressure readings are provided when the anaesthetist is busy and whenever an access to his/her patient is difficult. However, erroneous results may be produced in patients with irregular dysrhythmias, and nerve palsies may be produced with frequent measurements for prolonged periods.

An intravascular cannula / transducer amplifier / display system for arterial blood pressure measurement is indicated in seriously-ill patients, in patients with left ventricular disease or hypertension, in patients undergoing major or prolonged surgeries, in patients in whom deliberate hypotension is planned, in those in

whom sudden haemodynamic disturbances or substantial blood loss may occur and in morbidly obese patients. In clinical practice, mean arterial blood pressure, in most situations during direct blood pressure monitoring, can safely guide therapy. However, this requires great vigilance against displayed false readings not recognised due to lack of experience.

The electrocardiogram has been always used as a front-line monitor for the cardiovascular system, although it gives no indication of the adequacy of the circulation. From this point of view it lost its situation for the privilege of the pulse oximeter. Analysis of ECG rhythm requires a systematic approach acquired through training.

Detection of arrhythmias and ischaemia is diagnosed by 12-lead ECG, ambulatory ECG, exercise ECG or through ST segment analysis by 3 or 5 lead ECG. However, transoesophageal echocardiography (TOE) gives more consistent information of ischaemia, and may also show segmental wall motion abnormalities (SWMA). So, there is some risk that the ECG may provide a false sense of security because an unchanged ECG may not be a guarantee that the patient is not hypoxic, hypotensive or hyperbaric. If the anaesthetist considers why, how and when the ECG should be monitored, then ECG recording may be very fruitful.

Pulse oximeters are used as continuous, non-invasive, rapid-response monitors of arterial blood oxygenation in all patients during the perioperative period and in patients in intensive care units, specially those with cardiovascular or respiratory diseases. They are now considered front-line monitors as they display both

oxygen saturation and pulse rate and rhythm. They are also considered second-line monitors for oesophageal intubation and ventilator disconnection. As they may draw attention to life-threatening situations during anaesthesia, their perioperative use is recommended as a minimum monitoring standard. This is because no other monitor is equal to the pulse oximeter which non-invasively and safely provides a continuous indication of the adequacy of circulatory and respiratory functions.

Capnography is used in the operating room for continuous carbon dioxide waveform analysis from patient intubation to extubation and it is sometimes used in the recovery room. Measurement of end-tidal carbon dioxide tension by capnography can detect many equipment and patient-related problems which other monitors alone may fail to detect or may detect so slowly that patient safety may be compromised. Examples are diagnosis of a mal-functioning inspiratory valve, oesophageal intubation, kinking of the endotracheal tube, ventilator disconnection, hypotension, pulmonary embolism and increased endogenous carbon dioxide production due to sepsis, shivering or malignant hyperpyrexia. So, capnography can alert the anaesthetist to life-threatening conditions, when the anaesthetist is familiar with the device and its calibration.

The electronic thermometer: Measuring body temperature is highly recommended during neonatal and paediatric surgeries of substantial duration and during protracted surgeries in adults, particularly with exposed body cavities. It is also indicated with expected administration of large volumes of fluids and in operations with deliberate cooling and rewarming. It is also recommended for

elderly patients undergoing surgeries under general or regional anaesthesia. In addition to monitoring skin temperature, core temperature can be measured from the rectum, the lower oesophagus, the nasopharynx, the tympanic membrane, the urinary bladder or through the PAC. Ideal body temperatures can be maintained through titrating the balance between heat loss and heat gain.

Monitoring neuromuscular transmission ensures optimal paralysis during surgery and optimal recovery from paralysis at the end of surgery. Monitoring neuromuscular block has been possible by electromyography and mechanomyography. Recently, the ulnar nerve stimulator can provide monitoring for neuromuscular transmission through the analysis of the train of four pattern. All patients who have been given non-depolarizing muscle relaxants must be closely observed by trained personnel until they are conscious and have demonstrated adequate recovery from paralysis confirmed by the ability to sustain a five-second head-lift. There is a recent recommendation for the universal use of nerve stimulators to prevent residual neuro-muscular block in all patients. The nerve stimulator has important value for diagnosing delayed postoperative recovery.

For **monitoring anaesthetic depth**, the human monitors play a main role by clinical interpretation of signs of depth of general anaesthesia. Awareness during anaesthesia is simply prevented by little more anaesthetic than little less anaesthetic, guided by education and training. Recently, the Bispectral Index (BIS), as a modified EEG, has been promisingly used to track adequate

anaesthetic depth. A BIS value below 100 till 60 denotes an awake patient. With a value below 60, there is a very low probability of patient recall. The range between 60 and 50 may denote deep sedation or light anaesthesia, and below 50, the patient is usually unconscious. However, it should be known that explicit recall of intraoperative events is not entirely a reliable test of awareness. The unconscious storing of a traumatic memory known as implicit memory is diagnosed by retension of previously presented words during anaesthesia and can lead to post-traumatic stress disorder and can be prevented by providing adequate depth of anaesthesia.

For **monitoring the brain and spinal cord functions**, in addition to the awake testing and EEG monitoring including its BIS modification, modern development of electronics and microprocessors allow easy real-time monitoring of the nervous system functions by the physician.

The brain can respond to stimuli applied to peripheral or cranial nerves by evoked potentials, as somatosensory evoked potential, brainstem auditory evoked response, visual evoked response, and motor evoked potential. The somatosensory evoked potential is indispensable during many surgical procedures on peripheral nerves, nerve plexuses, during spinal corrective surgery or intracranial carotid endarterectomy. The brainstem auditory evoked potential can be a component of the feed-back closed-loop system to control general anaesthesia. The visual evoked response is classically used in procedures near the anterior visual pathways. The motor evoked response records the full length of central motor pathways of the brain and the spinal cord. Cranial nerve monitoring

can be used perioperatively for preservation of vision or hearing or other functions.

The intracranial pressure can be monitored by different devices including a fiberoptic epidural device. However, a ventriculostomy with an intraventricular catheter remains the gold standard for intracranial pressure monitoring.

Cerebral blood flow monitoring has been recently possible by the non-invasive transcranial Doppler device. It can be used during carotid endarterectomy and cardiopulmonary bypass to detect microemboli and to estimate relative cerebral blood flow.

Juglar venous bulb oxygen monitoring is useful for clinical assessment and management of global cerebral oxygenation based on monitoring arterial-juglar venous difference in oxyhaemoglobin content in patients with severe head injury.

Echocardiography depends on the characteristic of ultrasound and extends the anaesthetist and intensivist abilities for diagnosing cardiac anatomy and physiology functions. Transthoracic echocardiography imaging techniques include parasternal long and short axis views together with apical four-chamber and subcostal views. The quality of image may be unsatisfactory due to COPD, obesity or chest wall injury or chest wall changes with age. Transoesophageal echocardiography (TOE) imaging techniques include lower, mid and upper transoesophageal and epivascular views, and all types of diagnosing images are possible including transgastric views. Echo signals may be one dimensional (M-mode) or two-dimenstional (2-D). A three-dimensional (3-D) echo is being currently elucidated. Spectral

Doppler measures blood flow velocity either as Pulsed-wave or Continuous wave. Colour flow Doppler represents a 2-D echo image with superimposed colour coding of the Doppler shift created by moving red blood cells. TOE can be used for assessment of regional cardiac functions with detection of myocardial ischaemia, assessment of global function with measurement of cardiac output, assessment of cardiac anatomy with the blood flow pattern, assessment of congenital heart disease with efficiency of the surgical repair, detection of intracardiac air or thrombi, diagnosis of pericardial disease and guiding intra-aortic balloon pumping. Inspite of the valuable role played by TOE for diagnosis and during cardiac surgical repair, its role during general anaesthesia is limited. Hazardous problems of general anaesthesia for the cardiac patients are expected to take place during laryngoscopy and endotracheal intubation. Serious cardiovascular responses cannot be assessed by TOE because the probe is practically introduced in the oesophagus with imaging only after and not before endotracheal intubation. Then, the anaesthetist is left with the echo changes during maintenance which can be detected by simpler monitors. However, the value of preoperative patient assessment by echocardiography is a fundamental one.

Thromboelastographic coagulation analysis provides a new method for evaluation of the whole coagulation system from initial clot formation to clot retraction or dissolution. The basis of this method is that the current view of intrinsic, extrinsic and common coagulation systems is accused by inaccuracy and over-simplification ignoring the interactive nature of haemostasis as these

systems analyze separate components. So, thromboelastography measures the net result of both coagulation and fibrinolytic systems. It monitors the thrombodynamic properties of the blood as it is induced to clot under a low shear environment resembling sluggish venous blood flow.

The instrument consists of a simple cylindrical cup and a measurement pin which is attached to a calibrated torsion wire. A small sample of blood is placed in the cup and allowed to clot as the cup oscillates. The elastic shear modulus of the sample is measured as fibers composed of fibrin and platelets are formed and attach the cup to the pin which is monitored for motion. Graphic measurements are displayed on a screen.

To evaluate the graphic information displayed by the system, quantitative parameters of clot formation and lysis are measured. Clot formation can be quantitatively or qualitatively interpreted in terms of hypo-or hypercoagulable states. Abnormal patterns have been associated with coagulation factor deficiencies and functional platelet abnormalities.

Recently, an improved thromboelastography method (ROTEG) with less sensitivity to some handling issues has been introduced. One of the more common applications of either method is for detection of excessive fibrinolysis after liver transplantation. Recent computerization and automation of these instruments have improved their accuracy and have promised a wider scope of clinical applications.

Central and pulmonary artery catheters are used to monitor right and left ventricular filling pressures. Their placement

requires a certain level of experience to achieve the best monitored data and to prevent associated complications. The measurement of the central venous pressure needs a simple fluid manometer or the catheter may be attached to a transducer where values are displayed on a screen with zeroing and calibration. The pulmonary artery wave-forms can be also displayed on a screen. The central venous catheter or the pulmonary artery catheter is introduced through a central vein by percutaneous Seldinger technique. A displayed central pressure wave-form through a central venous catheter, shows a pattern of three upstrokes and two descents that correspond to certain events in the cardiac cycle. Monitoring can diagnose the presence of hypovolaemia and can be used for guiding volume replacement during major surgeries. The Swan-Ganz or pulmonary artery floatation catheter is used to measure the pulmonary capillary wedge pressure for monitoring left ventricular end-diastolic pressure as an indirect index of left ventricular end-diastolic volume. Cardiac output measurement, achieved through thermodilution using a pulmonary artery catheter and an appropriate output computer is usually both accurate and reproducible. This is useful in critically-ill patients to discriminate low and high cardiac output states. Mixed venous oxygen saturation can be continuously monitored via a fiberoptic bundle on the pulmonary artery catheter. This is an indicator of supply-demand relationship of oxygen and is inversely proportional to the oxygen extraction ratio. It is also useful for determination of ventilation/perfusion mismatching or blood shunting.

Intramucosal PH monitoring by gastric tonometry, has been used to reveal early gut failure in different shock states including hypovolaemic and septic shock. It monitors regional oxygen supply/demand relationship. Management of shock states by fluids and pharamcotherapy aims to normalize intramucosal PH. This is of supreme value when coupled with normalization of the oxygen supply/demand global relationship by goal oriented haemodynamic therapy.

Monitoring gas-exchange and respiratory mechanics is usually complementary to subjective information provided through medical history and physical examination of the patient.

Gas-exchange monitoring includes stroke volume, stroke index, cardiac output, cardiac index, stroke work, stroke work index, systemic vascular resistance, systemic vascular resistance index, pulmonary vascular resistance and pulmonary vascular resistance index. Other important gas-exchange parameters include arterial oxygen content, venous oxygen content, arterio-venous oxygen content difference, oxygen delivery, oxygen consumption, oxygen extraction ratio, oxygenation index, alveolar-arterial oxygen tension gradient, respiratory index, arterial/alveolar oxygen tension ratio, arterial-endtidal carbon dioxide tension gradient, ventilation/perfusion relationship and right to left shunt fraction. Monitoring gas-exchange abnormalities are derived from primary variables and additional parameters as haemoglobin concentration and body surface area deduced from body weight and height together with blood gas analysis.

Monitoring pulmonary function tests can explore abnormalities of ventilatory functions of the lungs and chest wall. The cornerstone of pulmonary function testing is clinical spirometry, defining lung volumes and capacities. These include tidal volume, inspiratory reserve volume, inspiratory capacity, residual volume, expiratory reserve volume, functional residual capacity, closing capacity, vital capacity and total lung capacity.

To identify airway obstruction or restriction, flow rates are determined by calculating the exhaled volumes during unit time intervals. Most commonly measured by spirometry are the volume exhaled in the first second, (expressed as absolute volume in liters or as a percentage of the forced vital capacity), the peak expiratory flow rate (obtained from the forced vital capacity), and the maximum breathing capacity (also known as the maximum voluntary ventilation).

Monitoring respiratory mechanics is achieved through measurements of compliance, airway resistance, the work of breathing and other parameters.

Computerized systems for continuous monitoring of dynamic and static compliance have been developed for adults and paediatrics and proved useful during the management by ventilatory support. The single tidal breath method using the static compliance technique is a common method used during mechanical ventilation. The multiple pressure-volume method has been developed as an extension of the single breath method to establish pressure-volume or compliance-volume curves. Effective compliance has been

recently pointed out for the measurement of static compliance in the passively ventilated patient.

Intrinsic airway resistance and effective airway resistance are measured using specific equations. As most airway resistance resides in the large and medium-sized bronchi, auto-PEEP can take place due to dynamic hyperinflation of the lung in COPD patients and can be measured.

The increased work of breathing can be clinically observed as the patient moves the chest and the abdominal wall using the accessory respiratory muscles when breathing loudly in an abnormal way. The total work of breathing is estimated more accurately by the measurement of pressure over-time. Campbell published a method for the measurement of the mechanical work of breathing in a spontaneously breathing subject. He constructed two pressure-volume diagrams during quiet inspiration and expiration. Then, he constructed a combined diagram to describe the total metabolic cost of the work of breathing in joules. In the spontaneously breathing patient, an imposed work of breathing could be measured by integration of the pressure-volume loop, using a modified Campbell diagram. This could measure the mechanical work and the metabolic cost of breathing performed with all modes of partial ventilatory assistance, all ventilators, all circuits and in all patients.

Recently, computerized pulmonary monitors are designed to allow easy determination of the work of breathing at the bedside for clinical purposes. Two work of breathing values are displayed; the patient work of breathing derived from the Campbell diagram and the ventilator work of breathing. The aim of the ventilatory support

is to titrate the balance between both components to a non-fatiguing patient overload.

Other respiratory mechanics include the respiratory drive, the respiratory time fraction, the pressure-time index and the pressure-time product. On-line side-stream spirometry has been recently designed using a flow-volume monitor providing flow-volume or pressure-volume loops as well as routine spirometric data for detection of pulmonary mechanics.

Monitors of class IV having sensed (by a device), collected and organized the data (by a device), interpret them (by a device) and then present the interpreted data to the physician. They use feedback open or closed loop systems including controllers to dose drugs to the patients to maintain desired target values. In spite of this, the data should be supervised by the attending physician, so that his/her skills may complement those of the controller and the monitor.

The major roles performed by the anaesthetist during administering general anaesthesia are the maintenance of drug induced unconsciousness, muscle relaxation and perioperative analgesia.

In either open or closed feedback loops, the difference between the input (target or desired) and the output (measured) values is treated as an integrated error to be corrected by the controller through changing anaesthetic concentration through a vaporizer or infusion rate through an infusion syringe or pump. This can be compared to an imaginary loop which includes the anaesthetist who corrects the error between the input and output

values by manually changing the vaporizer setting or the drug infusion rate.

For the control of unconsciousness, clinical signs are the only widely accepted criteria for assessment of anaesthetic depth. These include BP, HR, pupil size and motor activity. Such signs included in the Guedel classification were extensively used during the ether era, when anaesthetic depth in the non-paralyzed patient undergoing surgery could be assessed by lack of movement and adequacy of both respiratory and cardiovascular variables.

Recently, measured and desired variables for controlling anaesthetic depth include BP, $PETCO_2$, end-tidal anaesthetic concentration, evoked responses of various agents including EEG and its BIS modification and the auditory evoked response. Integrated errors between desired and measured values of such variables are corrected by controllers in the open or close-loop feedback systems. Although this concept has been applied by many authors, there is no absolute or gold standard for the clinical state of anaesthesia against which new methods for measuring its depth can be assessed.

For **controlling muscle relaxation** during general anaesthesia, a closed-loop has been used by different authors including a microcomputer, a neuromuscular monitor, a volumetric infusion device and the patient. Muscle relaxation is maintained by the controller calculating the drug infusion rate to achieve a target train of four ratio. Drug infusion is stopped 10 minutes before the end of surgery and reversal of muscle relaxation is achieved by neostigmine-atropine guided by a nerve stimulator.

Patient controlled analgesia denotes self-administration of small doses of narcotics by the patients when they experience pain. This approach is based on the premise that a negative feedback open-loop exists, composed of a microprocessor-controlled drug infusion pump triggered by depressing a button by the patient anticipating pain. When the pain is reduced or disappears, there will be no further demand of analgesics until pain returns; the patient providing the input for pain control

The system usually consists of an infusion device which allows on-demand bolus injection of the drug, with or without continuous background infusion. The size and rate of the bolus dose may be altered. Inadvertent over-dosage is avoided by limiting the size of individual boluses and the total dose administered within a minimal time between boluses (lock-out interval). The controls must be inaccessible to the patient or the relatives.

In addition to patient-controlled intravenous analgesia, the epidural space can share in pain control both in the postoperative period and during labour. Such patient-controlled epidural analgesia is effective and associated with patient satisfaction. Both techniques through the intravenous or epidural routes need training to minimize complications.

Patient controlled analgesia offers something more than just morphine. It offers the security of knowing that the patient has some control over her/his pain. It guarantees that the patient is checked every hour, and if pain is not under control, the nurse has immediate access to the Acute Pain Service.

Control strategies for a managed process may be simple, adaptive or intelligent. In simple control strategies, an error between the measured and desired values of a chosen variable is mostly corrected by a simple controller, where an integrated error acts as a performance index. Correction of the error is achieved through automatically and repeatedly changing the vaporizer setting or the device infusion rate. The limitations are the occurrence of oscillations and a failure to anticipate the surgical stimulus.

In adaptive control strategies, mathematical models are adapted according to the changing process. It takes into account the individual responsiveness of the patient to the administered drug and the changing responsiveness during its administration. One way of self-adaptive control is to include an estimator, in addition to the controller in the closed-loop in order to estimate the mathematical model process to help to achieve the desired output value very quickly. Another way is to optimize error correction processing quickly by the use of more than one controller. Self-adaptive strategies could expand the concept of automation.

Intelligent control strategies keep an output value in memory to predict the following output value according to history (on-line learning). Multivariable controllers provide the basis of multi-input/ multi-output (MIMO) intelligent control systems. This has been successfully applied for the simultaneous control of unconsciousness and muscle relaxation. An important example of the intelligent control strategy is the knowledge-based Fuzzy-logic controllers which depend on the simple rule "if x, then y", to attain a self-organizing system.

Applications of controllers in different areas of medicine have been added to their application in anaesthesia. Examples are control of insulin therapy in diabetes mellitus, administration of drugs as theophylline for bronchial asthma, administration of vaso-active drugs for arterial hypertension, administration of anticoagulants, antibiotics, antiarrhythmics and chemotherapeutic agents.

Diabetes mellitus, in its form requiring insulin treatment, results from partial or complete failure of the pancreas to produce insulin in response to elevated blood glucose level. While the classical controller is usually thought of as the doctor, in diabetes it is frequently the patient him/herself who makes the decision concerning the adjustment of insulin therapy, particularly on a day-to-day basis. Actually, the diabetic patient can be regarded as a multi-input / multi-output (MIMO) physiological model which contains several controllable and measurable variables. The patient's diet and the dosage of insulin can be considered as control variables to be adjusted to maintain a balance between energy supply and expenditure with blood glucose being regulated at levels set by the clinician.

Control schemes are either in the form of a closed-loop which determines the insulin infusion rate in accordance with the monitored blood glucose level, or an open-loop which involves pre-programmed short-term insulin delivery algorithm independent of a glucose sensor (feed-forward control). The closed-loop system which monitors the blood glucose level of the patient continuously and administers appropriate amounts of insulin calculated by the

controller, is known as the artificial pancreas. The open-loop system includes a computer which receives, stores and processes patient-entered data with respect to self-measured glucose concentrations, estimated dietary intake and anticipated physical exercise. Some systems provide therapeutic advice based on past as well as current blood or urine glucose concentrations and insulin data. On this basis, short-term feed-forward control and day-to-day feed-back control strategies can be designed.

Theophylline therapy is used for bronchodilatation in the treatment of acute and chronic bronchial asthma. The therapeutic levels of this drug represent a narrow blood concentration range (10-20 mcg/ml) and symptoms of toxicity may occur at higher concentrations.

Model-based control is the basis of the adaptive control system employed in the simulation of theophylline therapy. The infusion regimen is computed to achieve and maintain a target theophylline concentration in a pharmacokinetic model. The model parameters are initially set to the best estimates available given the prior information about the patient. When a measurement of the patient response is available, the parameters of the individual patient, and the model parameters are adapted to the new parameter estimates. The infusion rate is then automatically adjusted as required to move the concentration to the target level. In the implementation of the adaptive control system, the infusion regimen would be automatically delivered by means of a computer-controlled infusion or syringe pump. Previous simulation studies of adaptive control of theophylline therapy utilized the simple strategy

of adjusting the maintenance infusion rate with a goal of achieving the target theophylline concentration in the steady state.

Controlling potassium therapy may be used to treat hypokalaemia in surgical and medical diabetic patients during their management. Automatic feed-back control may provide a system for rapid, safe correction of plasma potassium concentration. In an experimental study in dogs, plasma potassium was monitored continuously by means of a selective electrode inserted into the femoral artery. The electrode output was fed to an amplifier and subsequently passed through a filter and the electrode was calibrated. The animal was heparinized to prevent clot formation on the electrode tip. The control algorithm was written on a personal computer, and used a controller with separate control equation for potassium chloride infusion. The program was displayed on a screen which gave the current status of the infusion rate. With an automatic feed-back control, plasma potassium was monitored continuously and the signal compared with the desired plasma concentration. The resulting error controlled the infusion rate to the desired concentration at various rates, dictated by the controller constants. Such a system may introduce an acceptable approach for its application for potassium therapy in human clinical settings in the future.

Bioengineering is the science which deals with the interface between the equipment and the patient. Anaesthesia and intensive care are heavliy dependent on the hospital engineering system. The supply of oxygen, suction, N_2O and medical breathing air should be permanently maintained. When using a piped system, oxygen

supply failure alarm and oxygen analyzer alarm in the breathing circuit are complementary. When using oxygen cylinders, an oxygen pressure failure device must be installed.

Loss of electrical supply needs prompt restoration by an automatic emergency generator. If a fire develops, the fire triad should be broken and a sound alarm system allows rapid evacuation of working personnel.

Before commencing any anaesthetic, the anaesthetist should check all equipments including airway instruments, suction, the floweter, the vaporizer, the ventilator and monitors. The checkout process is similar to the check performed by the pilot checking the exterior of the aircraft by walking around it and testing its internal monitors before taking off. This process is time consuming and may be automated in the future.

Ergonomics is a science which deals with the interface between the equipment and the medical practitioner denoting his study at the work-place.

Dispersion of pieces of equipment around the anaesthetist with complex displays and alarms has the potential to inhibit vigilance and to cause human errors. The integration of monitored data and alarms into one compact display provides an ergonomic advantage. A brief glance to the compact display provides sufficient information without distraction.

Minimal monitoring standards have been fixed by the World federation of the Societies of Anaesthesiologists according to international standards of safe anaesthesia, which are flexible

enough to allow improvement in anaesthetic practice in any country, no matter what the economic status might be.

Minimal standards should be fixed for monitoring the machine or the patient.

If a piped oxygen system is used, there must be an oxygen supply failure alarm added to an oxygen analyzer. If oxygen cylinders are used, there must be suitable oxygen supply failure alarm fitted to the anaesthetic machine. With mechanical ventilation, there should be a reliable mechanism for detecting failure of ventilation. Machine monitoring at patient include regular on-line analysis of volatile agent concentrations, in the inspiratory or expiratory limbs of the breathing circuit or both.

For patient monitoring, the important "device" is the presence of a vigilant anaesthetist. The patient needs simple monitoring if s/he belongs to ASAI class, the operation is simple, brief, minimally invasive and needs no muscle relaxation. The anaesthetist carefully observes the reservoir bag with fingers on the pulse and measuring BP by a manual sphygmomanometer. A pulse oximeter is also essential for monitoring oxygenation. More escalated monitoring is needed for patients of ASA II or more class, with longer operations, extremes of age or body weight, expected blood loss and fluid shifts together with the need of muscle relaxation.

The amount of monitoring devices should be tailored to the patient needs including ECG, capnography, thermometry, peripheral nerve stimulation or monitoring of expired anaesthetic concentrations. Spirometry, invasive monitoring of cardiac filling

pressures by central venous or pulmonary artery catheters and monitoring ABG's may be added if mandatory.

Morbidity and mortality occurring in the early postoperative period remains fairly constant and is largely preventable. The anaesthetist must accompany the patient to the recovery room after operation. The recovery room should be provided with facilities that assume sufficient patient care, through proper designing and sufficient staff-members. Patient discharge criteria should satisfy patient safety and communication between the theatre and the postoperative ward important.

Regular programs for teaching the principles and the proper use of monitors should be initiated and maintained in every hospital, including the use of simulators.

Risk assessment depends on an analysis of all the components within the system; both the patient and healthcare providers (the anaesthetists, the surgeons and the nursing staff). The assessment of the patient is carried out by the ASA physical status, different scoring systems, different investigations and monitors specially the human monitors. Machine monitoring should not be ignored. For assessment of the risk of anaesthetists for inducing adverse events affecting patient outcomes, there was no reliable way of testing the practical ability of a minimum standard; except for instituting systems for continuous medical education with monitoring their learning and practical skills throughout their career. Recently, however, simulators, using specific and sensitive scenarios for crisis management, can objectively monitor the vigilance and performance of anaesthetists and to top up their

abilities. The performance of surgeons can be monitored by the cumulative sum method that evaluates sequential outcomes for a given surgical procedure to be plotted against adverse outcome over a period of time. A refinement of this method incorporates patient-related risk factors in the analysis of outcome to be compared with predicted outcomes. Other healthcare providers, including nurses, are monitored for improved risk assessment through organised systems aiming to continuously provide high quality of services. In general, the aim of any monitoring program of risk assessment should be to improve objectivity and to reduce subjectivity of the process, enhanced by the use of mathematical modelling.

10 Recommendations

10. Recommendations

I. Class I "human monitors" use human intelligence to interpret measured parameters within acceptable limits and their management if they lie outside these limits. This way, the anaesthetist, through a global approach can administer and maintain anaesthesia in a fashion tailored to the individual patient requirements. The intensivist can also use "human monitors", through a global approach, to manage the individual ICU patient. Human monitors should occupy a leadership position for other classes of monitors, showing that human intelligence, actually, masters technology intelligence.

II. The art of monitoring can attain its goals through different approaches including:

1. Improving registration of medical records of the patients.
2. Setting minimum monitoring standards both for the machines and the patients by anaesthetic authorities at different locations.
3. Fixing protocols, guidelines and rules together with documenting and circulating them to all those who are concerned.
4. Getting the best value of each medical dollar spent in purchasing medical monitors and high tech pieces of equipment.

5. Improving continuous medical education and training programs including the proper use of simulators for crisis management.

III. Future attention should be given for simple, adaptive and intelligent controlling systems. We should start feeling concern about closed-loop control systems in anaesthesia and drug therapy. We should be courageous enough to face the responsibility of using these systems. A controller, like a ventilator, can provide us with free hands for patient management during anaesthesia and drug therapy. In the operating theatre or the intensive care unit, we never allow the ventilator to run unattended. This should be "the same" for the controller. In this way both the ventilator and the controller offer extensions to the anaesthetist or the intensivist, not their replacement. Only when we approach controllers in this way, will we be able to take advantage of what they offer.

Acronyms

Acronyms

ABASI	Australian Bureau of Air Safety Investigation
ABG	Arterial blood gas
AC	Alternating current
ACCESS	Anaesthetic Computer Controller Emergency Situation Simulator
ACT	Activated clotting time
AIMS	Australian Incident Monitoring Study
ALI	Acute lung injury
Alpha angle	Clot formation rate
ACSS	American College of Surgeons' Scale
APN	Acute pain nurse
APS	Acute pain service
APT	Acute pain team
aPTT	Activated partial thromboplastin time
ARDS	Acute resipratory distress syndrome
ASA	American Society of Anesthesiologists
ASD	Atrial septal defect
A-V	Arterio-venous (malformations)
AVDL	Cerebral arterio-venous difference of lactate
$AVDO_2$	Arterial-juglar venous difference in oxyhaemoglobin content
BAEP	Brain-stem auditory evoked potential
BAER	Brain-stem auditory evoked response
BP	Blood pressure
BIS	Bispectral Index
CaO_2	Arterial oxygen content
$Ca\text{-}vO_2$	Arterio-venous oxygen content difference
CBF	Cerebral blood flow
CC	Closing capacity
CcO_2	Ideal end-capillary pulmonary arterial oxygen content
CGMS	Continuous glucose monitoring system
CI	Cardiac index
CIEA	Continuous infusion epidural analgesia
C_L	Lung compliance

CNS	Central nervous system
CO	Cardiac output
CO_2	Carbon dioxide
COPD	Chronic obstructive pulmonary disease
CPAP	Continuous positive airway pressure
CPB	Cardiopulmonary bypass
CPRI	Cardio-pulmonary risk index
CRI	Cardiac risk index
Cstatic	Static compliance
C_T	Total system compliance
C_{TH}	Thoracic compliance
CUSUM	The cumulative Sum method
Cv	Closing volume
CvO_2	Mixed venous oxygen content
CVP	Central venous pressure
CWD	Continuous Wave Doppler
2-D	Two-dimentional (echocardiography)
3-D	Three-dimentional (echocardiography)
DBS	Double burst stimulation
DC	Direct current
d-Down	Delta down
DO_2	Oxygen delivery
d-Up	Delta up
E	Error
ECG	Electrocardiography
EEG	Electroencephalography
EF	Ejection fraction
EMG	Electromyography
ENT	Ear, nose and throat
EP	Evoked potential
ERV	Expiratory reserve volume
ETT	Endotracheal tube
FAC	Fractional area change
FDA	Food and Drug Administration
FDP	Fibrin degradation product
FEF_{50}	Forced expiratory flow at 50% of forced vital capacity

FEV1	Volume exhaled in the first second
FFP	Fresh frozen plasma
$F1F_{50}$	Forced inspiratory flow at 50% of forced vital capacity
FiO_2	Inspired oxygen fraction
FRC	Functional residual capacity
Fvapr	Required vaporizer concentration
FVC	Forced vital capacity
GCS	Glasgow coma scale
GIT	Gastro-intestinal tract
Hb	Haemoglobin
HDU	High dependency unit
HF	High frequency
HPV	Hypoxic pulmonary vasoconstriction
HR	Heart rate
HRV	Heart rate variability
Hz	Hertz
IASP	International Association for the Study of Pain
IC	Inspiratory capacity
ICP	Intracranial pressure
ICU	Intensive care unit
IJV	Internal jugular vein
I/P	Input
IPPV	Intermittent positive pressure ventilation
IRV	Inspiratory reserve volume
JAMA	Journal of American Medical Association
JVB	Juglar venous bulb
K+	Potassium ions
K	Coagulation time
LA	Left atrium
LAP	Left atrial pressure
LF	Low frequency
LOI	Lactate oxygen index
LV	Left ventricle
LVEDP	Left ventricular end-diastolic pressure
LVEDV	Left ventricular end-diastolic volume
LVOT	Left ventricular outflow tract

LY	Lysis
MA	Maximum amplitude
MAC	Minimal anaesthetic concentration
MAC	Monitored anaesthesia care
MAP	Mean arterial pressure
MBC	Maximum breathing capacity
MEAC	Minimal effective analgesic concentration
MEP	Motor evoked potential
MF	Median frequency
MIMO	Multi-input-multi-output
MMG	Mechanomyography
M-Mode	Motion-mode
MVV	Maximal voluntary ventilation
NMB	Neuromuscular blockade
NMBD	Neuromuscular blocking drug
N_2O	Nitrous oxide
NO	Nitric oxide
NSAID	Non-steroidal anti-inflammatory drug
OI	Oxygenation index
O/P	Output
O_2	Oxygen
O_2ER	Oxygen extraction ratio
P	Proportional (controller)
PA	Pulmonary artery
$P(A\text{-}a)O_2$	Alveolar-arterial oxygen tension gradient
$P(a/A)O_2$	Arterial-alveolar oxygen tension ratio
PAC	Pulmonary artery catheter
$PaCO_2$	Arterial carbon dioxide tension
PaO_2	Arterial oxygen tension
PAO_2	Alveolar oxygen tension
Palv	Alveolar pressure
PAP	Pulmonary artery pressure
PATM	Atmospheric pressure
PaV	Arterial halothane tension
Paw	Airway pressure
Pb	Barometric pressure
Pbr N_2OC	Brain concentraion of N_2Oin MAC units

Pbr vr	Required brain tension of halothane
PCA	Patient-controlled analgesia
PCEA	Patient-controlled epidural analgesia
PCIA	Patient-controlled intravenous analgesia
PCWP	Pulmonary capillary wedge pressure
PD	Proportional derivative or differential controller
PEEP	Positive end-expiratory pressure
PEEPi	Intrinsic positive end expiratory pressure
PEEPtot	Total positive end-expiratory pressure
PEF_{25}	Peak expiratory flow over the first quarter of the forced vital capacity
PEF_{50}	Peak expiratory flow over the second quarter of the forced vital capacity
PEF_{75}	Peak expiratory flow over the third quarter of the forced vital capacity
PEF_{50-75}	Peak expiratory flow over the middle half of the forced vital capacity
PEFR	Peak expiratory flow rate
$PETCO_2$	End-tidal carbon dioxide tension
PHi	Intramucosal PH
PI	Proportional integral (controller)
PID	Proportional integral derivative or differential (controller)
PIF	Peak inspiratory flow
PIP	Peak inspiratory pressure
Ppl	Intrapleural pressure
Pplat	Plateau pressure
Pr	Artifical airway resistance pressure
PRI	Pulmonary risk index
PRQ	The predictive respiratory complication quotient
PRST	Arterial blood pressure, heart rate, sweating and tears score
PT	Prothrombin time
PTI	Pressure time index
PTP	Pressure time product
PvO_2	Venous oxygen tension of haemoglobin

PVR	Pulmonary vascular resistance
PVRI	Pulmonary vascular resistance index
PWD	Pulsed-Wave Doppler
Qs/Qt	The shunt fraction of cardiac output
Qz	Electrical impedence estimate of cardiac output
R	Reaction time
RA	Right atrium
Raw	Airway resistance
Reaw	Effective airway resistance
RESAC	Real-time expert system for advice and control
RI	Respiratory index
ROTEG	Rotation thromboelastography
RQ	Respiratory quotient
RR	Respiratory rate
RV	Right ventricle
RV	Reserve volume
RVOT	Right ventricular outflow tract
SaO_2	Arterial oxygen saturation of haemoglobin
SEF	Spectral edge frequency
SI	Stroke index
$SjvO_2$	Juglar venous oxygen saturation
SNP	Sodium nitroprusside
SOFLC	Self-organising Fuzzy-logic controller
SpO_2	Pulse oximeter haemoglobin oxygen saturation
SQF	Cardiac output scaling factor
SQI	Signal quality index
SR	Suppression ratio
SSEP	Somatosensory evoked potential
SV	Stroke volume
SVA	Alveolar-ventilation scaling factor
SVR	Systemic vascular resistance
SVRI	Systemic vascular resistance index
SvO_2	Mixed venous oxygen saturation of haemoglobin
SW	Stroke work
SWI	Stroke work index
SWMA	Segmental wall-motion abnormalities

TBI	Traumatic brain injury
TCD	Transcranial Doppler
TEG	Thromboelastography
Ti	Inspiratory time
TIVA	Total intravenous anaesthesia
TLC	Total lung capacity
TNG	Trinitroglycerine
TOE	Transoesophageal echocardiography
TOF	Train of four
TO_2	Oxygen transport
TS	Trauma Score
Ttot	Total time
TURP	Transurethral resection of the prostate
UK	United Kingdom
USA	United States of America
V	Flow rate
VAS	Visual analogue scale
VC	Vital capacity
Vdt	Flow per unit time or volume
VEP	Visual evoked potential
VER	Visual evoked response
VO_2	Oxygen consumption
$VO2/DO_2$	Oxygen consumption-delivery relationship
V/Q	Ventilation-perfusion ratio
VSWI	Ventricular stroke work index
V_T	Tidal volume
Wi	Inspiratory work per breath
WBCLI	Whole blood clot lysis index
WOB	Work of breathing
WOBi	Imposed work of breathing
WOBp	Patient work of breathing
WOBv	Ventilator work of breathing
W_T	Total work

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